

BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

IN THE MATTER OF THE
APPLICATION BY DEUEL HARVEST
WIND, LLC FOR A PERMIT OF A
WIND ENERGY FACILITY AND A 345-
kV TRANSMISSION LINE IN DEUEL
COUNTY

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CERTIFICATE OF SERVICE

EL18-053

I hereby certify that true and correct copies of

John Homan's response to PUC Staff's 1st set of data request

were served electronically to the Parties indicated below, on February 25th, 2019, addressed
to:

Ms. Kristen Edwards Staff Attorney South Dakota Public Utilities Commission 500 E. Capitol Ave. Pierre, SD 57501 Kristen.edwards@state.sd.us (605) 773-3201 - voice	Ms. Lisa M. Agrimonti - Representing: Deuel Harvest Wind Energy LLC Attorney Fredrikson & Byron, P.A. 200 South Sixth Street, Suite 4000 Minneapolis, MN 55402-1425 lagrimonti@fredlaw.com (612) 492-7000 - voice (612) 492-7077 - fax
Ms. Amanda Reiss Staff Attorney South Dakota Public Utilities Commission 500 E. Capitol Ave. Pierre, SD 57501 amanda.reiss@state.sd.us (605) 773-3201 - voice	

Date: 2-25-19

John Homan
Intervenor
4114 12th Ave. NE
Watertown, SD 57201
Homan1971@gmail.com

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**INTERVENOR JOHN HOMAN'S
RESPONSE TO PUC STAFF'S FIRST SET
OF DATA REQUESTS**

EL18-053

Below, please find John Homan's responses to Staff's First Set of Data Requests. The original request is restated and followed by my response.

1. Provide copies of all data requests submitted to or by you and copies of all responses provided to those data requests. Provide this information to date and on an ongoing basis.

Yes, we will include that information and forward it to you.

2. Refer to SDCL 49-41B-22.

A. Please specify particular aspect/s of the applicant's burden that you intend to personally testify on.

Applicant has the burden of proof that the project will not have negative impacts on, or cause the following issues:

1. The project's effect on environmentally sensitive area that will destroy the habitat for the existing wildlife, many different species of songbirds, waterfowl, eagles, turkeys, the list is long.
2. Our deer population that our property and trees support year round.
3. We have a large population of monarch butterflies, and the effects on that population.
4. The impact it could have on the Northern Long-eared Bat, and its habitat and feeding areas.
5. The effect of the project on Monighan Creek and its drainages, and the concern for the springs that feed it. It's a home to the Northern Redbelly Dace, a threatened species.
6. The fire dangers from turbine fires and how it could devastate acres of wildlife habitat, trees, shrubs, grassy areas, and nearby homes and buildings.
7. The concern for the safe usage of our landing strip, Homan Field, which is permitted and FAA approved.
8. The negative impact that the project would have, because of the close proximity of industrial wind towers to our property. Such as how it would affect the health and well being of our family's usage and enjoyment of the property in a manner that we have for

the past 30 years - our usage has no negative effects on any neighboring properties. Also the negative effect it would have on the property value, the value that is attributed to the use of the property as well as the monetary value.

B. Please specify particular aspect/s of the applicant's burden of proof that you intend to call a witness to testify on.

I have no witnesses at this time but would reserve the right to add witnesses at a later date, and to call them to testify remotely if needed.

3. Refer to SDCL 49-41B-25. Identify any "terms, conditions, or modifications of the construction, operation, or maintenance" that you would recommend the Commission order. Please provide support and explanation for any recommendation.

I would like to have the applicant provide an independent geological and hydrology study of the project area within a minimum distance of two miles of Monighan Creek, and within a two mile distance from our property boundaries. It is critical since Monighan Creek is a spring-fed, free flowing creek and our property contains 4 spring-fed dams that could be impacted by contamination from the process of construction and the long term damage that could be caused by the impacts of these massive turbine foundations and the ground vibrations caused by the operations of the towers. One of our dams is a natural restocking fishery.

Monighan Creek is one of a few homes to the Northern Redbelly Dace minnow which is on the state threatened species list.

I would like the applicant to show locations of all aquifers and the depths to those aquifers. We request an aquifer study and report to be submitted with their application.

A. Specifically, what mitigations efforts would you like to see taken if this Project is constructed?

- 1. That the towers be set back a minimum of 2 miles from environmentally sensitive areas, sensitive because of the concentration of wildlife and the forested and riparian areas.**
- 2. One and one half mile setbacks from non-participating residences, especially in the case of multiple residences in concentrated areas.**
- 3. One half mile set back from all non-participating property lines.**
- 4. Zero shadow flicker on non-participating residences, and any outbuildings on non-participating properties. A maximum of 15 minutes per day on non-participating properties at property boundaries.**
- 5. A maximum of 35 dBA at non-participating residences.**

6. A maximum of 38 dBA at any non-participating outbuilding that are for human use, such as workshops, garages, barns, etc.
7. A maximum of 45 dBA at non-participating property lines.
8. The limits of noise to be verified by an independent testing company paid for by the applicant.
9. A one mile set back to the west of Homan Field runway, and a two mile set back to the north, south, and east to accommodate the flight path for safe operations.
10. A 1500 foot set back from all public roads and right-of-ways for safety concerns - i.e. ice throw, etc.

4. Please list with specificity the witnesses that you intend to call. Please include name, address, phone number, credentials, and area of expertise.

I have no witnesses at this time but would reserve the right to add witnesses at a later date, and to call them to testify remotely if needed.

5. Do you intend to take depositions? If so, of whom?

None at this time, but I reserve the right to submit depositions that were taken in our on-going lawsuit against the Deuel County Board of Adjustment for conflicts of interest during the Deuel Harvest permitting process.

Date: 2-25-19

John Homan

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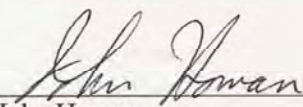
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* **INTERVENOR JOHN HOMAN'S**
* **RESPONSES TO APPLICANT'S FIRST**
* **SET OF DATA REQUESTS**

* **EL18-053**
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Below, please find John Homan's responses to Applicant's First Set of Data Requests. The original request is restated and followed by my response.

1-1) Provide copies of all data requests submitted by PUC staff to you in this proceeding and copies of all response to those data requests. Provide this information to date and on an ongoing basis.

1-2) Identify the address of your permanent residence (where you reside).

John Homan
4114 12th Ave NE
Watertown, SD 57201

1-3) Identify all property you own within the vicinity of the Deuel Harvest North Wind Farm ("Project") and the location (by section, township, and range) of such property. Are there any habitable buildings on the property you own?

John Homan = 224 acres - Sec 20, Twp. 116, R 48
John Homan = 138 acres - Sec 15, Twp. 116, R 49
Homan Steel Constr, Inc = 310 acres - Sec 32, Twp. 116, R 47
House under construction, a 48' x 70' building, includes office, shop, and storage.

1-4) If you have a residence in the vicinity of the Project, identify whether you live at the residence throughout the entire year and, if not, how many months of the year you reside at the residence.

None at this time.

1-5) Identify how you use your land, including, but not limited to, whether you use your land for agricultural purposes.

1/4

The land in section 32 = some farm land, pasture, CRP, and used to support wildlife, and for outdoor recreation.

1-6) Identify any sensitive or unique features of your property that you assert would be impacted by the Project.

Description of section 32 property is as follows:

The property is crossed by Monighan Creek, in the half mile we have 1.3 miles of creek. The entire valley is covered with a variety of natural growth, shrubs, trees, native plants and grasses, as well as many acres of planted trees and shrubs. The valley transitions to rolling hills and drainages.

In addition to the free flowing, spring fed creek, we have developed 4 spring fed dams with bordering grasses, cattails, trees, and shrubs. One of the dams is a approx. 6 acre natural restocking fishery.

It is a haven for all kinds of wildlife!

The property in section 20 is a mix of pasture, crp, farm land, and several acres of trees and shrubs. The property includes an approx. 35 acre lake/slough that is a waterfowl haven, within the designated duck nesting habitat area.

The property in section 15 is pasture land dotted with cattail sloughs.

1-7) Describe your concerns regarding the Project.

The close proximity of these massive, industrial wind turbines will be detrimental to all the birds and wildlife.

As the proposed project shows, we will have approximately 9 towers within a mile of the property, and approximately 17 towers within 2 miles of the property in section 32. There will be towers adjacent to my property in section 20. The closest one approx. 600' from our property line.

I am concerned that the close proximity of the towers will harm the usage of the property, by all the wildlife, local and migratory.

It will be very harmful for the usage of the property that we have worked for an invested in for 30 years.

The work and enjoyment that our entire family has invested in, including our children and grandchildren. We are concerned about the safety and health of our family in the normal use of the property that we are accustomed to.

The property in section 32, includes approximately 50 acres of trees and shrubs. It was a playground for our children and it is also now for our grandchildren!

We are concerned about fire danger to our persons and trees and shrubs, because of the proximity of wind turbines. In a rural situation like this, a fire could not be controlled in a location like this.

The landing strip that we are constructing would not be safe to use, and safety was a concern of our zoning board before they granted us the permit, as well as a great concern to our family and anyone else that would be using the landing strip.

I am also greatly concerned about possible damage to, and contamination of, our numerous springs and aquifers.

1-8) Describe what mitigation measures would address the concerns you identified in response to Request 1-7 and whether any of the mitigation measures identified by the Applicant in its Application could address any of your concerns.

Towers could be moved or removed to accommodate our concerns, without any harm to the overall project. Already many original towers have been moved or removed. Towers need to be moved to allow for the safe usage of our landing strip. Towers should be moved to prevent damage to the environmentally sensitive areas that support many species of wildlife. Towers also need to be moved to prevent problems from noise, infrasound, and shadow flicker for ourselves and many other non-participants to prevent health problems, quality of life problems, and loss of property values.

1-9) Identify any documents, information, education, training, or professional experience you have relied upon to form your opinions concerning the Project. Where you have relied upon documents or other tangible materials, please provide such documents and/or materials.

I would like to reserve the right to provide documents at a future time. Information is readily available from many sources, studies, and news reports of issues caused by industrial wind turbines.

My professional experience is from traveling all over the United States in the course of our construction business and hearing about the negative effects of living near industrial wind projects.

1-10) Identify any witnesses, including expert witnesses, you plan to have testify on your behalf. For each witness (including expert witnesses), please provide a resume or statement of qualifications of the witness(es), identify the subject matter regarding which the witness will testify, and identify and provide any exhibits the witness will refer to or introduce.

I would reserve the right to add witnesses at a later time.

1-11) Are you asserting that the Project will negatively impact your property value? If so, provide copies of any appraisals or other valuations that have been conducted for such property within the last ten years.

I am absolutely asserting that the project will negatively affect the value of our property in the respect of the purpose and use that the property was developed for, in the past, and for the future. Value of property is not always based on monetary value, usage value is determined by different individuals. I do not have a current appraisal at this time, but would reserve the right to submit later.

1-12) Identify any communications, written or otherwise, you have had with units, officials, and/or representatives of local, state, and/or federal governments or agencies concerning the Project.

a) For any written communications, provide a copy of the communication; and

I will include written letters to the county boards and presentations at hearings. I will submit others that may have been sent as I find them.

b) For any unwritten communications, provide the date of the communication, the persons involved, and the subject matter of the communication.

I have personally talked to Deuel County Commissioners, at different times, while county setbacks etc. were being determined, and at Commissioners meetings. Also many conversations with members of the zoning board, at the zoning board meetings, concerning my landing strip, over a 6 month period in 2017. Most of the conversations were about how my landing strip would affect the possible future industrial wind towers.

1-13) Your Application for Party Status does not identify your interest in this proceeding. Please briefly explain your interest in this proceeding.

Explained in 1-7.

1-14) Please state the address where you reside.

4114 12th Ave NE

Watertown, SD 57201

1-15) Does Homan Steel Construction, Inc. ("Homan Construction") own the property legally described as the W1/2 Section 32-116-47, Glenwood Township, Deuel County, South Dakota ("Glenwood Property")? If so, please describe the Homan Construction business activities that occur on the Glenwood Property.

Yes, it is used as an office, shop, and equipment storage for farming and construction activities, as well as recreational activities.

1-16) On July 31, 2017, Deuel County issued a building permit, Attachment 5, for a "new 24' x 40' house" on the Glenwood Property. With respect to the proposed house, please state a) the status of construction; b) the intended purposes for the residence; c) whether the house has a certificate of occupancy; and d) whether, if completed, the house is occupied.

Construction to be completed spring 2019.

1-17) On September 11, 2017, Deuel County issued a Special Exception Permit, Attachment 6, for construction of "an airplane landing strip for private use" on the Glenwood Property ("Private Landing Strip"). With respect to the Private Landing Strip, please state a) the status of construction; b) the intended purposes for the air strip; c) whether the air strip has been used; and d) the intended use of the air strip, including frequency and timing of use.

Construction to be completed spring 2019. The intended purpose and usage will be for our family's use for transportation to and from the farms and surrounding recreation areas. For use by friends and business associates if requested. For use by other local residents if requested, and for any emergency uses necessary. For use by airplanes and ultralights.

1-18) Describe your experience and qualifications related to piloting an aircraft.

I am not a licensed pilot.

1-19) Describe the type of business engaged in by and ownership of Homan Steel Construction, Inc.

Homan Steel Construction, Inc. owners John and Teresa Homan.

I have been in the construction business as a subcontractor and general contractor since 1970. Grain storage handling, grain elevator construction, wood framed and steel frame buildings - farm and commercial, concrete construction. We have built projects from North Carolina and Georgia to Oregon and California, from Canada border to Texas valley, from Michigan to New Mexico. We have traveled extensively through the United States due to our construction business.

1-20) Referring to Attachments 1 and 2, did you submit these attachments to the Clear Lake Courier?

I did provide maps from Invenergy, and supplied information included.

1-21) Does Attachment 3 depict the location of the Private Landing Strip and location of the

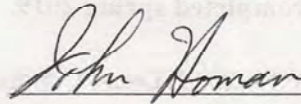
new house on the Glenwood Property?

That is correct.

This transition includes 3 letters of communications in response to your request.

Labled A, B, C.

Date: 2-25-19



John Homan

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Deuel County Commission Members and concerned parties,

I am writing this letter in regards to, and because of my concerns about the proposed wind tower project in Deuel County.

I currently live near Watertown, but I own property in Deuel County, some of which is northwest of Gary. I need to point out that I do not consider myself an outsider. I grew up on a farm in the county, went to school in Clear Lake, have always done business and my banking at DNB, and have many relatives in the county. In our construction business, I have worked with and for farmers and agricultural business's my entire life, and have a pretty good understanding of it.

I am not in favor of these industrial wind towers for several reasons. One reason being the proposed setbacks. The setbacks as currently proposed, I believe would negatively impact many residences and landowners. They should be greatly increased. These large wind turbines will negatively affect safety, health, well being, property values and overall quality of life for the community.

This area is very unique in many respects. In its geography, its creeks and trees, its hills and valleys, its wide open spaces and open views, its clean air etc.. It is a big part of the reasons people choose to live here, to farm here, to raise livestock, and to raise families here. I have seen more than enough of our country to know that this area is special. I've had many people from Watertown and other places, tell me how unique this area is and how they enjoy coming out. We, referring to my family, and all the people living around the entire area, get to enjoy the creek drainages, the trees, the lakes, the sloughs, all the wildlife that we have in the area, including deer, turkeys, pheasants, even bald eagles, and all kinds of birds if you take the time to look and enjoy. Another thing we wouldn't want to lose is the view of the night sky with little or no light pollution, it is amazing and everyone should check it out with your kids or grandkids. The sun rises and sunsets should not have to be viewed by anyone through the obstruction of a 500' wind tower. I'm sure there are many other areas in the county that many people feel the same way about. These things may not seem important to some people now, but at some time in their lives, priorities change and they will be important.

These huge industrial wind towers will forever change the views and the landscapes for everyone, and for their children and grandchildren!

I would like to touch on the property rights issues. I understand that all property owners should have the right to use their property as they choose, as long as it does not negatively affect surrounding property owners. Many things have restrictions such as water, air pollution, noise pollution, as well as building heights, in rural as well as urban areas. Ordinances seem more strict for cell phone towers than they are for these much larger and much more dangerous wind towers.

People buy property for many reasons, not just economic but also quality of life reasons. Home owners and other property owners should feel that they have the right to maintain their quality of life as they chose, and that someone else should not have the right to negatively affect it. For me personally, I have put an awful lot of time and money into enhancing and developing my property for the benefit of the wildlife and the environment, and the farmland quality, for my family as well as others. I hope it has also benefitted other people in the surrounding community.

I believe most people would not have built homes or acreages if wind towers would already have been in place. I think it will greatly restrict any further development in the rural areas or even in the towns that are in any close proximity to the wind towers. I personally would not carry through with plans to build a house or any business in the area if it is in the vicinity of industrial wind towers. Please consider the rights of all property owners who want to enjoy their homes as they are currently.

There would also be the fairness issue to all that would be impacted if the project went ahead. I would think that individual rural home owners and all property owners, would have the right to the same setbacks as others. If Lake Cochran residences are granted a two mile setback, I would think that Clear Lake, Gary, or any other town or even rural residences and any non participating properties would be entitled to the same rights under county protection. I feel that county government should protect everyone's property values. If someone wanted to grant a variance for a closer setback to his own property, that could be a personal choice. I personally feel that if you were in the position of having towers placed on all sides of your own property, a 2 mile setback would not be enough.

I haven't even touched on the health and safety issues and effects of industrial wind towers. Damage can be done in a quite extensive area because of structural failure. Ice that forms on the blades can fly off; ice that we know can be an issue in this area. Despite what the wind companies would like everyone to believe, there is a lot of info and research available on the various subjects if you take the time to check it out.

I would not want to subject my kids or grandkids to any of these issues if I didn't have to, and I assume most other people wouldn't either. I have to ask, would you personally want your own families living close to these huge wind towers? The potential for increased profit to some in the community should not justify such risks to health and safety for many others.

Let me make the point that I would in no way consider these wind towers as an agricultural project. This is strictly an industrial project and should be looked at as such. You folks have a big responsibility to all the property owners in the county.

In regards to the project and the companies, there are several questions that need to have complete and accurate answers, not just vague soothing words from the wind companies. There are cases where wind projects have been idled or abandoned, what happens and what are the responsibilities of the wind companies?

If they lose tax incentives is the project even viable, do they file bankruptcy and walk away?

If the company goes bankrupt, what happens?

If they sell to another company, what happens?

If the second or third company goes bankrupt, what happens?

What happens to payments to the landowners, are they guaranteed perpetually, if the company goes bankrupt, are the agreements null and void, or does a new company have the right to negotiate down?

If the towers are abandoned, I believe it would not be economically feasible to take down, scrap out, or move to rebuild. It would probably be cheaper to build new towers somewhere else. It may be more expensive to remove the entire structure than it was to build it. I believe it would financially break a lot of landowners to have to remove the towers on their own. The wind companies should therefore be bonded for the most extreme situation.

I have traveled through and worked in many parts of this country in the last forty some years and spent a lot of time in rural areas. I have never met anyone who was glad to be in any close proximity to a wind tower project. I have had many people relate negative stories and opinions, because of health problems and concerns, as well as aesthetic reasons, which to many may not sound as important.

I do understand the economic reasons that a project like this sounds attractive to many people, as the supposed increase in tax revenues. But, I do think there will be an economic and development drawback because of it, and a decrease in some land values and loss of other developments that would affect tax revenues.

At first, a large project like this sounds good for the county, but I sincerely hope you take a look at the long term aspect of it, and the overall effect to the community, which I hope you already have. Please ask yourself if you would personally want to live or have your families live next to a large wind tower which will change your landscape and life forever.

With all respect and sincerity, John Homan

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Letter To Editor=

I would like to express my opinion about how the zoning board meeting of Jan. 22nd was conducted. In my opinion it was a complete sham with a predetermined result by the zoning board with the help of the wind tower company. The zoning board, who's job it is to protect all the citizens of the county, appears to be nothing but a rubber stamp for the wind company. We have a copy of a letter to the board from Invenergy, dictating how the meeting should be conducted, even to limiting any opposition presenters to the 3 minute limit!

An issue that will severely affect hundreds of people and the entire county for generations, did not have to be limited to one meeting for any good reason! They even limited the number of speakers. Is there a limit to the number of people who's lives will be changed by this industrial wind project?

For a special exception to plant trees to close to a property line, can and would be opposed by an adjacent landowner and they would not be limited to 3 minutes! But for a special exception permit for a 500' wind tower, 550' from my property line, the board can limit my list of opposing reasons to 3 minutes, and then still ignore the reasons! For a house permit in the county, they require details about the exact location and details of the foundation, they did not even have one question about the massive foundation design for a 500' wind tower, how it might affect the local aquifers, underground springs, or possibly pollute our creeks and or wells.

The board obviously did not take the time to do their due-diligence for this concern, as well as many others that would need to be addressed in the sitting of all individual towers. This should be a priority of the board, but they are ignoring it. As I understood from the boards statement, they do not intend to even allow any opposition from adjacent landowners when the wind company applies for a permit for one or all of the 250 500'+ wind turbines, this would be unbelievable!

From my personal experience, it took me approx. 6 months and 5 zoning board meetings for me to be granted a permit for a grass airport landing strip on my property. There was no time restrictions for anyone opposing the project, and they were allowed to oppose it at multiple meetings if they wanted, am I the only one that sees a problem here? By the way, the first question I was asked by the board chairman, when I applied for the landing strip permit, was "how will it affect wind towers", there were no wind towers and there were no permits for wind towers!

The board all stated at the opening of the meeting that they have no conflicts of interest in regards to the wind tower project, from my experience, I personally doubt that. Does having signed a wind tower contract constitute a conflict of interest, you be the judge. State ordinance states that any predetermined bias or potential monetary gain by a public official involved in a decision, constitutes a conflict of interest.

At the 1-22nd meeting the board denied any opposing speakers to defend their statements but gave every opportunity to the wind tower company to rebut any or all issues they disagreed with. There are many other issues about the meeting that may be covered at another time.

I would like to reiterate, it is the duty of the zoning board "to protect the health , welfare, and property value of all the citizens of the county. It is not their duty to make it easier for an industrial wind tower company to make more money at the expense of many in the community.

John Homan

To the editor;

All residents of Deuel County need to be aware of and involved in what is about to happen that will change the county forever. I am referring to the project that could cover the area with 500' industrial wind towers. But the supporters of the project like to refer to this as a "wind farm". There is nothing agricultural about this. The wind tower companies will turn the county into an industrial park and then they will be gone!

I am writing this letter because of my serious concerns for the future of all of the county as well as my own property. I am one of those absentee landowners, but one that does not support wind towers for monetary gain. I currently live near Watertown but spend as much time as possible in Deuel County. I do not consider myself an outsider. I grew up on a farm in the county, went to school in Clear Lake, have done business, and have many relatives in the area. In our construction business, I have worked with and for farmers and agricultural business's my entire life and have a pretty good understanding of it.

This area is very unique in many respects. In its geography, its creeks and trees, its hills and valleys, prairies, open spaces and open views, lakes and sloughs, its clean air, etc.. It is a big part of the reasons people choose to live here, to farm and ranch -raise livestock here, and to raise families here. I have seen more than enough of the rest of our country to know that this area is special. I have had many visitors tell me what a beautiful area this is because of the terrain and the wildlife and the peacefulness. There are many other areas in the county that other people feel the same way about.

Whether you live in Clear Lake, Gary, or any other town or on a farm or ranch or acreage, everyone will be affected by 500' wind towers. Every drive in the country, every quiet evening enjoying our great outdoors, every time you go out hunting, fishing on our many lakes, camping, or just out watching the wildlife or our many birds, you will never be out of sight nor probably out of sound of industrial wind towers! Every horizon you would look at would include looking at wind towers! The sunrises and sunsets should not have to be viewed by anyone through the obstruction of a 500' wind tower. Your children and grandchildren should not have to try to look at the night sky through a veil of blinking red lights. I believe you would be able to see 500' wind towers from about every point in the county.

I have traveled through and worked in many parts of the country in the last forty some years and spent a lot of time in rural areas. I have never met anyone who was glad to be in any close proximity to a wind tower project. I have had many people relate negative stories and opinions because of health issues and concerns, as well property value problems and aesthetic reasons. I do understand the economic reasons that a project like this sounds attractive to some, as the supposed increase in tax revenue, but I do believe there will be economic and development drawbacks because of it and a decrease in land and residential values because of wind towers.

People buy property for many reasons, not just economic but also quality of life reasons. Home owners and other property owners should have the right to maintain their quality of life as they have chosen and someone else should not have the right to negatively affect it. For me personally, I have put

an awful lot of time and effort into enhancing and developing my property for the benefit of wildlife and the environment and farmland quality, for my family as well as the surrounding community. I believe most people would not have built homes or acreages if wind towers would have already been in place. I think it will greatly restrict any further development in the rural areas or even in towns that are in any close proximity to industrial wind towers. Another consideration is the health and safety issue effects of industrial wind towers. Please take some time to check these concerns of many people. Despite what the wind companies would like you to believe, there is a lot of legitimate concerns and problems directly resulting from wind towers. Ask yourself, would you want your own family living next to 500' wind towers. The potential for increased profits for a wind tower company or a few in the community should not justify risks to health and safety for many others. I would not want to subject my kids or grandkids to any of these risks and I assume most other people wouldn't either.

Some may feel wind turbines are beneficial "green" energy and that the harms they will bring to the area are justified, these giant wind turbines will likely never make up for the carbon footprint their construction creates. The only benefit from them is to the wind companies in the form of tax credits, and possibly to landowners who give up control of their land in exchange for some payments from the wind companies, but even for the landowners, any income from wind towers could be offset by many negative effects on crops or land uses and values.

These huge industrial wind towers will forever change the views and landscapes for everyone, and for their children and grandchildren! Some of your children and or grandchildren will never know how beautiful this area of the country was before it was turned into an industrial wind energy park. Everyone, participants and nonparticipants, should ask themselves, what have I done, or further yet, what have I not done to protect the quality of life in Deuel County!

I firmly believe that there will be a time when most of the folks in the county will regret the decision to turn the county into an industrial wind project!

John Homan

BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

IN THE MATTER OF THE
APPLICATION OF DEUEL HARVEST
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY

* GARRETT HOMAN'S RESPONSE TO
* STAFF'S FIRST SET OF DATA
* REQUESTS TO INTERVENORS
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EL18-053

Below, please find Garrett Homan's response to Staff's First Set of Data Requests to Intervenors. The original request is restated and followed by my response to that request.

- 1-1) Provide copies of all data requests submitted to or by you and copies of all responses provided to those data requests. Provide this information to date and on an ongoing basis.

The Applicant's first data request to Garrett Homan is attached to this response, and I will continue to provide all future correspondences.

- 1-2) Refer to SDCL 49-41B-22.
a. Please specify particular aspect/s of the applicant's burden that you intend to personally testify on.

Particular aspects of the applicant's burden I intend to testify on include:

1. The project as proposed does not comply with 49-41B-22 (3) since proposed turbines to the northwest, west, and southwest of our family's airstrip (western half of section 32 in Glenwood township) pose a substantial threat of serious injury or death to users of the airstrip (family, friends, approved users, and the public in emergency situations).
2. The project as proposed does not comply with 49-41B-22 (3) since the minimum setbacks used for siting do not meet the wind turbine manufacturer's (GE) recommendations for the required safety distances surrounding turbines in freezing weather to mitigate hazards associated with ice throw. This puts the safety of neighbors and the general public using roads at risk.
3. The project as proposed does not comply with 49-41B-22 (2) and (3) since construction, operation, and decommissioning of the turbines poses a threat of serious injury to the environment and the social and economic condition of current and future inhabitants as well as health and welfare of the inhabitants.

- b. Please specify particular aspect/s of the applicant's burden of proof that you intend to call a witness to testify on.

None at this time.

- 1-3) Refer to SDCL 49-41B-25. Identify any “terms, conditions, or modifications of the construction, operation, or maintenance” that you would recommend the Commission order. Please provide support and explanation for any recommendations.
- a. Specifically, what mitigation efforts would you like to see taken if this Project is constructed.

1. In regards to protecting the safety of users of our airstrip, I request the Commission order terms of the project to include:

a) no turbine sites under a one-sided (biased to the East) traffic pattern airspace sized for category B aircraft, and

b) no turbine sites within 10 rotor diameters (4,170 ft or .8 statute miles) of the runway and imaginary approach surfaces for the runway.

Regarding a), the dimensions of the traffic pattern airspace for our airstrip, defined per standards provided in FAA order JO 7400.2L, are 1.5 nautical miles (1.73 statute miles) from the north end, south end, and east side of the runway and .25 nautical miles (.29 statute miles) from the west side of the runway.

Regarding b), the imaginary approach surfaces for our runway, defined per the standards provided in 14 CFR 77.19 for utility runways with visual approaches, extend 5,000 ft from each end of the runway and expand to a width of 1,250 ft centered about the extended centerline. The 10x rotor diameter distance is applied from the outer boundaries of this shape comprised of an approach surface to the south, the runway, and an approach surface to the north. These safe setbacks currently effect turbine sites 106, 107, 108, 117, 123, and 124 from the application layout maps. See the appended figure showing these dimensions and our runway simply illustrated on an excerpt of the application layout map. This could be simplified into a rectangular shape extending 1 mile west, 1.75 miles north, 1.75 miles east, and 1.75 miles south of the extents of the airstrip runway surface.

2. In regards to protecting neighbors and the general public from risk of ice throw, I request the Commission order terms of the project to include minimum setbacks from non-participating property lines or public right of ways of at least 1100 ft to satisfy the recommendations to reduce risk from ice throw provided in “GE Power and Water,

Technical Documentation, Wind Turbine Generator Systems 1&2MW Platform, Safety Manual” (safety manual).

3. In regards to protecting the environment and participants’ and non-participants’ health and safety, I request the Commission order terms of the project include a state-managed 24-7 hotline and response department for the intended purpose of providing a means for the public to report environmental, health, and safety issues (such as oil leaks or other pollution, ground water contamination, excessive noise and shadow flicker, road or property damage from ice throw or turbine failures, fire, etc.) observed during project construction and operation and to coordinate the appropriate independent assessments and corrective actions. This hotline and response department should be funded by the applicant via an escrow account for the duration of the project, but managed by the state to ensure the public’s best interest is being served and to remove any potential for the applicant to delay or mishandle reports due to financial incentives.

- 1-4) Please list with specificity the witnesses that you intend to call. Please include name, address, phone number, credentials and area of expertise.

None are planned at this time, but I reserve the right to call witnesses at a later date.

- 1-5) Do you intend to take depositions? If so, of whom?

None are planned at this time.

Date 2/24/19



Garrett Homan
Intervenor
5669 Maple Grove Road
Hermantown, MN 55811
garhoman@gmail.com

**BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA**

**IN THE MATTER OF THE
APPLICATION OF DEUEL HARVEST
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY**

* **APPLICANT’S FIRST SET OF DATA**
* **REQUESTS TO GARRETT HOMAN**
* **EL18-053**
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Below, please find Deuel Harvest Wind Energy LLC’s (“Applicant”) First Set of Data Requests to Garrett Homan. Please submit responses within 10 business days or promptly contact the undersigned to discuss an alternative arrangement.

- 1-1) Provide copies of all data requests submitted by PUC staff to you in this proceeding and copies of all responses to those data requests. Provide this information to date and on an ongoing basis.
- 1-2) Identify the address of your permanent residence (where you reside).
- 1-3) Identify all property you own within the vicinity of the Deuel Harvest North Wind Farm (“Project”) and the location (by section, township, and range) of such property. Are there any habitable buildings on the property you own?
- 1-4) If you have a residence in the vicinity of the Project, identify whether you live at the residence throughout the entire year and, if not, how many months of the year you reside at the residence.
- 1-5) Identify how you use your land, including, but not limited to, whether you use your land for agricultural purposes.
- 1-6) Identify any sensitive or unique features of your property that you assert would be impacted by the Project.
- 1-7) Describe your concerns regarding the Project.
- 1-8) Describe what mitigation measures would address the concerns you identified in response to Request 1-7 and whether any of the mitigation measures identified by the Applicant in its Application could address any of your concerns.
- 1-9) Identify any documents, information, education, training, or professional experience you have relied upon to form your opinions concerning the Project. Where you have relied upon documents or other tangible materials, please provide such documents and/or materials.

- 1-10) Identify any witnesses, including expert witnesses, you plan to have testify on your behalf. For each witness (including expert witnesses), please provide a resume or statement of qualifications of the witness(es), identify the subject matter regarding which the witness will testify, and identify and provide any exhibits the witness will refer to or introduce.
- 1-11) Are you asserting that the Project will negatively impact your property value? If so, provide copies of any appraisals or other valuations that have been conducted for such property within the last ten years.
- 1-12) Identify any communications, written or otherwise, you have had with units, officials, and/or representatives of local, state, and/or federal governments or agencies concerning the Project.
- a) For any written communications, provide a copy of the communication; and
 - b) For any unwritten communications, provide the date of the communication, the persons involved, and the subject matter of the communication.
- 1-13) In the last five years, how often have you visited South Dakota? Of those visits, how many times did you use aircraft as transportation?
- 1-14) What locations in South Dakota have you visited in the past five years?
- 1-15) How many times in the past five years you have landed an aircraft in South Dakota and, of those times, how many landings were at the Clear Lake Airport?
- 1-16) Describe any ownership interest you have in, or right to use, a personal aircraft.
- 1-17) Describe any interest you have in Homan Steel Construction, Inc. ("Homan Construction") or the W1/2 Section 32-116-47, Glenwood Township, Deuel County, South Dakota ("Glenwood Property")
- 1-18) In your January 15, 2019 comment to the PUC, you state that your "family is currently constructing a 2,350 foot long turf runway, named Homan Field, on the western half of section 32 in the Glenwood township of Deuel County" ("Private Landing Strip"). With respect to the Private Landing Strip:
- a) What is the intended use of the Private Landing Strip?
 - b) You state that turbines on the northeast side of the proposed Private Landing Strip have been removed and "This allows for a one-sided traffic pattern to be flown without flying over any wind turbines, except turbine number 108 which is under the margin the FAA standards establish on the far side." i) What FAA standards are you asserting apply? ii) Is turbine location No. 108 the only turbine location you assert will interfere with the Private Landing Strip? If not, please explain.

- c) You include a discussion of and figure showing approach surfaces. What regulations are you asserting establish these surfaces for the Private Landing Strip?
- d) What experience, education and training do you have regarding wake turbulence and wind shear?
- e) Provide any correspondence to or from the Federal Aviation Administrative regarding the Private Landing Strip.

Dated this 13th day of February 2019.

By /s/ Lisa Agrimonti

Mollie M. Smith

Lisa M. Agrimonti

FREDRIKSON & BYRON, P.A.

Attorneys for Applicant

200 South Sixth Street, Suite 4000

Minneapolis, MN 55402

Phone: (612) 492-7000

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BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

**IN THE MATTER OF THE
APPLICATION OF DEUEL HARVEST
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY**

* **GARRETT HOMAN'S RESPONSE TO**
* **APPLICANT'S FIRST SET OF DATA**
* **REQUESTS**
*
* **EL18-053**
*
*

Below, please find Garrett Homan's response to Deuel Harvest Wind Energy LLC's ("Applicant") First Set of Data Requests to Garrett Homan. The original request is restated and followed by my response to that request.

- 1-1) Provide copies of all data requests submitted by PUC staff to you in this proceeding and copies of all responses to those data requests. Provide this information to date and on an ongoing basis.

The Staff's first data request to Garrett Homan is attached to this response, and I will continue to provide all future correspondences.

- 1-2) Identify the address of your permanent residence (where you reside).

5669 Maple Grove Road, Hermantown, MN, 55811

- 1-3) Identify all property you own within the vicinity of the Deuel Harvest North Wind Farm ("Project") and the location (by section, township, and range) of such property. Are there any habitable buildings on the property you own?

I do not own property in the vicinity of the project.

- 1-4) If you have a residence in the vicinity of the Project, identify whether you live at the residence throughout the entire year and, if not, how many months of the year you reside at the residence.

I do not have a residence in the vicinity of the project.

- 1-5) Identify how you use your land, including, but not limited to, whether you use your land for agricultural purposes.

This question is broad. Assuming the question is in regards to land in the vicinity of the project, I do not own land there. Regarding how we use my parents' property in the vicinity of the project, my family loves to spend time there enjoying nature in the peace and quiet – such as hunting and fishing, watching the variety of birds and wildlife, developing habitat, stargazing with the clear skies, camping, hiking, canoeing, developing habitat, planting and harvesting pumpkins, picking fruit, and generally enjoying nature and our time together.

- 1-6) Identify any sensitive or unique features of your property that you assert would be impacted by the Project.

Unique features of my parents' property that will be impacted by the project include – safe use of the airstrip we're building; abundant wildlife, habitat, and hunting; the local ecosystem, including Monighan Creek and its drainage areas; and our enjoyable use of and future development of the property.

- 1-7) Describe your concerns regarding the Project.

I have many concerns regarding the Project:

- 1. The safety of my family, friends, and myself in using our airstrip.**
- 2. Noise and shadow flicker negatively affecting the wildlife and driving them away from the habitat we have worked so hard to develop on the property.**
- 3. Noise and shadow flicker and blinking lights negatively affecting my family's use and enjoyment of the property**
- 4. The large grouping of wind turbines affecting the safety of all inhabitants with respect to masking tornadic activity in the area and reducing the ability of meteorologists to track storms and tornados and provide accurate warnings.**
- 5. Risks of ice throw and turbine damage hurting people and damaging property, as well as risk of fires that can't be put out in a timely manner devastating habitat and property and putting human life at risk.**
- 6. The ecological impact associated with construction, operation, and decommissioning – driving wildlife away, directly killing birds, bats, bugs, and butterflies, contaminating ground water and the sensitive Monighan Creek and its drainage systems, pollution from oil leaks, and the**

substantial landfills that will be required to handle a mountain of non-reclaimable materials used in wind turbines.

- 1-8) Describe what mitigation measures would address the concerns you identified in response to Request 1-7 and whether any of the mitigation measures identified by the Applicant in its Application could address any of your concerns.

Keeping a rectangular area measuring 1.0 miles to the west and 1.75 miles to the north, east, and south of our runway free of turbines would allow use of our runway by family, friends, and the general public without substantially affecting flight safety. This would also provide the benefit of protecting the wildlife, habitat, ecosystem, and enjoyable use of our property.

In general throughout the project, increasing the minimum setbacks from property lines to be 1,100 feet would mitigate the risk to non-participating neighbors and the public right of ways for ice throw, by meeting the manufacturers safety recommendations.

In regards to protecting the environment and participants' and non-participants' health and safety, I request a State-managed 24-7 hotline and response department for the intended purpose of providing a means for the public to report environmental, health, and safety issues (such as oil leaks or other pollution, ground water contamination, excessive noise and shadow flicker, road or property damage from ice throw or turbine failures, fire, etc.) observed during project construction and operation and to coordinate the appropriate independent assessments and corrective actions. This hotline and response department should be funded by the Applicant via an escrow account for the duration of the project, but managed by the State to ensure the public's best interest is being served and to remove any potential for the applicant to delay or mishandle reports due to financial incentives.

- 1-9) Identify any documents, information, education, training, or professional experience you have relied upon to form your opinions concerning the Project. Where you have relied upon documents or other tangible materials, please provide such documents and/or materials.

I have read many online articles about the safety concerns of flying around wind turbines, including articles and summaries of the wind turbine accident in Highmore, SD in 2014 that resulted in 4 fatalities. I have attached an article from the Airplane Owners and Pilots Association about the safety effects wind turbines can have on aircraft especially in the vicinity of airports.

I have also spoken with aerial applicators, one being Denny Meyer from Steier Ag Aviation in Whittemore, IA, a highly experienced commercial pilot, who shared his harrowing tale of flying in and around wind turbines and how they “shake the hell out of you.” His business has decided to no longer service land in or around wind turbines due to the substantial safety risk they pose to him and his sons who fly for the family business as well.

I have also read wind turbine wake effect research papers published for the wind turbine industry to use for siting turbines to maximize performance and mitigate turbine blade fatigue life issues from upwind turbine wakes. There are numerous such research papers available online that demonstrate turbine wakes have aerodynamic effects that should be addressed properly, one such that I have attached is Vermeer et al, “Wind Turbine Wake Aerodynamics”, Progress in Aerospace Sciences, Volume 39, Issues 6 and 7, August to October 2003.

I have also educated myself by using the COPA/SMS Report No. 1101, Aviation Safety-risk Assessment of the Effect of Wind Turbines on General Aviation Aircraft (see references), summarizes the results and determinations of a 9-member panel that consisted of experts representing pilots COPA (the Canadian Owners and Pilots Association, a group representing airplane owners and pilots), aviation safety (SMS Aviation Safety Inc.), the Canadian civil aviation authorities (Transport Canada and Nav Canada), and a wind energy consulting engineering firm (Genivar). The report was produced with the intent of being used by policy makers, industrial wind turbine project developers, and pilots to manage the risks imposed on aviation by industrial wind turbines. I have permission to use this report to help in promoting aviation safety and have attached the report to this response.

Regarding safety around wind turbines in freezing weather and icing conditions, I have reviewed the “GE Power and Water, Technical Documentation, Wind Turbine Generator Systems 1&2MW Platform, Safety Manual” which is included in the public docket for the OPSB Application for Seneca Wind and can be easily found online. The safety manual considers icing a “special danger” and states “it is advisable to cordon off an area around the wind turbine generator system with the radius R^* during freezing weather conditions, in order to ensure that individuals are not endangered by pieces of ice thrown off during operation. $R^* = 1.5 \times (\text{hub height [m]} + \text{rotor diameter [m]})$ (Recommendation of the German Wind Energy Institute DEWI 11/1999).”

- 1-10) Identify any witnesses, including expert witnesses, you plan to have testify on your behalf. For each witness (including expert witnesses), please provide a resume or statement of qualifications of the witness(es), identify the subject matter regarding which the witness will testify, and identify and provide any exhibits the witness will refer to or introduce.

None are planned at this time. However, I reserve the right to call witnesses at a later date.

- 1-11) Are you asserting that the Project will negatively impact your property value? If so, provide copies of any appraisals or other valuations that have been conducted for such property within the last ten years.

I do not own property in the vicinity of the project. However, I do assert that the project will negatively affect the property value of my parents' property, both monetary and the intrinsic value.

- 1-12) Identify any communications, written or otherwise, you have had with units, officials, and/or representatives of local, state, and/or federal governments or agencies concerning the Project.

a) For any written communications, provide a copy of the communication; and

I have submitted statements to the Deuel County Board of Adjustment and made verbal statements during the Project permitting process. My submittals can be found on the docket maintained for that hearing by the Deuel County auditor.

b) For any unwritten communications, provide the date of the communication, the persons involved, and the subject matter of the communication.

None that I am aware of.

- 1-13) In the last five years, how often have you visited South Dakota? Of those visits, how many times did you use aircraft as transportation?

In the last five years, I have visited South Dakota numerous times per year (exact numbers unknown). My wife, children, and I love spending time in South Dakota enjoying the beautiful area I grew up in. We come back to South Dakota often for family birthdays and

get-togethers, holidays and vacation days, and spending time on our family's property hunting, canoeing, hiking, camping, gardening, watching wildlife, and enjoying nature in the peace and quiet. In the past 5 years, I believe I've only flown to South Dakota 1 or 2 times. We look forward to flying much more often in the future because of the availability of our airstrip.

1-14) What locations in South Dakota have you visited in the past five years?

This question is overly broad. We have visited too many locations to list them all. Most of our time is spent at our family's property in Deuel County (Section 32, Township 116, Range 47; Section 20, Township 116, Range 48; Section 15, Township 116, Range 49) and Watertown, Clear Lake, Gary, Lake Cochrane, Pierre, Rapid City, and the Black Hills.

1-15) How many times in the past five years you have landed an aircraft in South Dakota and, of those times, how many landings were at the Clear Lake Airport?

In the past 5 years, I believe I've only flown to South Dakota 1 or 2 times, and I have not landed at the Clear Lake Airport.

1-16) Describe any ownership interest you have in, or right to use, a personal aircraft.

As a private pilot, I can rent single engine land airplanes from any Fixed Based Operator or other rental company following a basic checkout procedure with their instructor. I currently am a member of and use airplanes from the Duluth Flying Club in Duluth, Minnesota. I have been considering buying an airplane or entering into a shared ownership for the past few years, since it has been a life goal of mine to own an airplane since I was young. I have also been considering buying a powered parachute or ultralight aircraft for use at our airstrip. I love South Dakota and I love flying and I can't think of many things more enjoyable than flying over that countryside in an open cockpit ultralight or parachute.

1-17) Describe any interest you have in Homan Steel Construction, Inc. ("Homan Construction") or the W1/2 Section 32-116-47, Glenwood Township, Deuel County, South Dakota ("Glenwood Property")

I have no ownership interest in Homan Steel Construction.

1-18) In your January 15, 2019 comment to the PUC, you state that your “family is currently constructing a 2,350 foot long turf runway, named Homan Field, on the western half of section 32 in the Glenwood township of Deuel County” (“Private Landing Strip”). With respect to the Private Landing Strip:

a) What is the intended use of the Private Landing Strip?

The airstrip is intended to serve operations ranging from ultralight aircraft up to 4+ seat general aviation airplanes. The airstrip is intended to be used by myself, my family and friends, and public use will be allowed with prior approval. The construction and operation of the airstrip is also intended to provide a benefit to South Dakota and the general aviation community in the form of a charted navigational aide and, more importantly, a safe landing site in the event of an in-flight emergency.

b) You state that turbines on the northeast side of the proposed Private Landing Strip have been removed and “This allows for a one-sided traffic pattern to be flown without flying over any wind turbines, except turbine number 108 which is under the margin the FAA standards establish on the far side.” i) What FAA standards are you asserting apply?

My comments submitted to the docket contain clarifying information:

What is the traffic pattern airspace required in order to use Homan Field? Since the Deuel Harvest North Wind project layout has changed since the Special Exception Permit approval, wind turbines to the northeast of Homan Field have been removed by the developer. This allows for a one-sided traffic pattern to be flown without flying over any wind turbines, except turbine number 108 which is under the margin the FAA standards establish on the far side of the runway. The dimensions of the traffic pattern airspace for Homan Field, as defined by FAA standards established in FAA order JO 7400.2L, are 1.5 nautical miles (1.73 statute miles) from each end and the east side of the runway and .25 nautical miles (.29 statute miles) from the west side of the runway. Figure 2 [attached at the end of my response] illustrates the airport environment around Homan Field superimposed over a section of the project layout map. The yellow dashed line illustrates the traffic pattern airspace boundary.

ii) Is turbine location No. 108 the only turbine location you assert will interfere with the Private Landing Strip? If not, please explain.

My comments submitted to the docket contain clarifying information:

What are safe setback distances from wind turbines for general aviation operations? The expert panel reviewed the available research and addressed numerous potentially catastrophic risks associated with wind turbines, as obstacles for low flying aircraft and sources of wake turbulence and wind shear. The expert panel made recommendations for minimum setback standards for industrial wind turbines near airports and airstrips should include:

- **a restriction on constructing wind turbines within the distance equal to 7-10 rotor diameters from the runway or approach surfaces and**
- **the area of land under the traffic pattern airspace is free of wind turbines.**

In Figure 2 [attached at the end of my response], red lines are used to show the a 10x rotor diameter setback from the runway and approach surfaces. As shown above, the wind turbines numbered 106, 107, 108, 117, 123, and 124 from the application layout maps do not meet the recommended setback standards for wake turbulence and wind shear and therefore pose a substantial risk to serious injury or death for those flying into or out of Homan Field.

- c) You include a discussion of and figure showing approach surfaces. What regulations are you asserting establish these surfaces for the Private Landing Strip?

My comments submitted to the docket contain clarifying information:

Title 14 of the Code of Federal Regulations Part 77 defines the federal regulations for the Safe, Efficient Use, and Preservation of the Navigable Airspace. The standards used to define approach surfaces for runways are defined per section 77.19. An approach surface is applied to each end of each runway based upon the type of approach available or planned for that runway end. For Homan Field, a preliminary assessment of the approach surfaces shows the approach surfaces are sized as follows. The inner edge of the approach surface is the same width as the primary surface and it expands uniformly to a width of 1,250 feet. The approach surface extends for a horizontal distance from the ends of the runway of 5,000 feet at a slope of 20 to 1. In Figure 2 [attached at the end of my response], purple lines sketch the dimensions for the approach surfaces.

- d) What experience, education and training do you have regarding wake turbulence and wind shear?

As a private pilot, I have received training on the basics of aircraft wake turbulence and wind shear and the significant effects they can have on flight safety and the importance of avoidance. As an aerospace engineer, I have a Bachelor's of Science in Aerospace Engineering and a basic professional understanding of aerodynamics and fluid dynamics.

- e) Provide any correspondence to or from the Federal Aviation Administrative regarding the Private Landing Strip.

I have included a figure I had sent to the FAA showing the proposed location details during the permitting process (attachment included below). I no longer have the sent emailed.

Date

2/25/19



Garrett Homan

Intervenor

5669 Maple Grove Road

Hermantown, MN 55811

garhoman@gmail.com

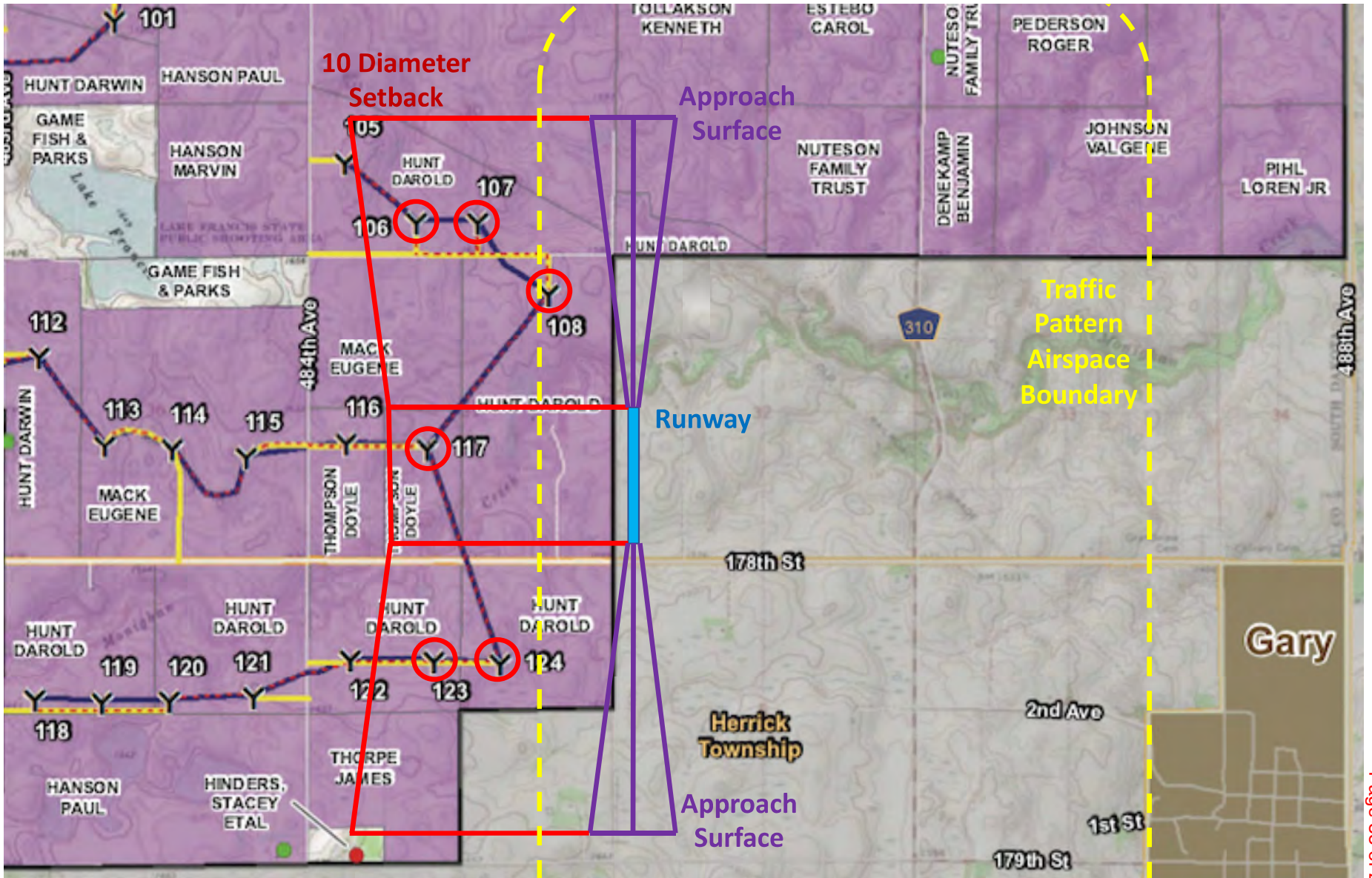
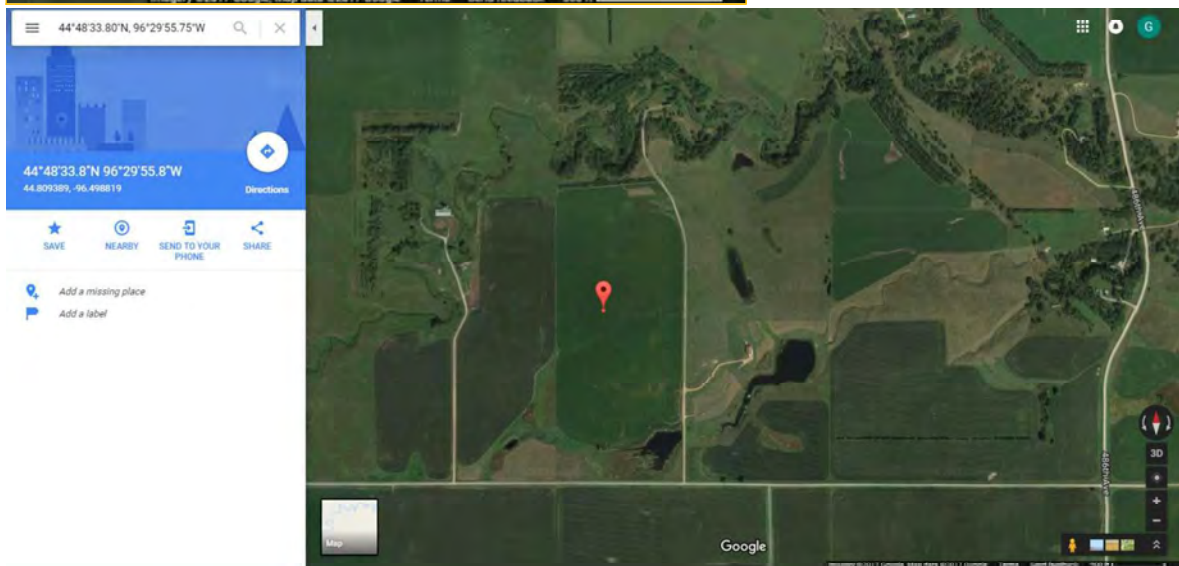
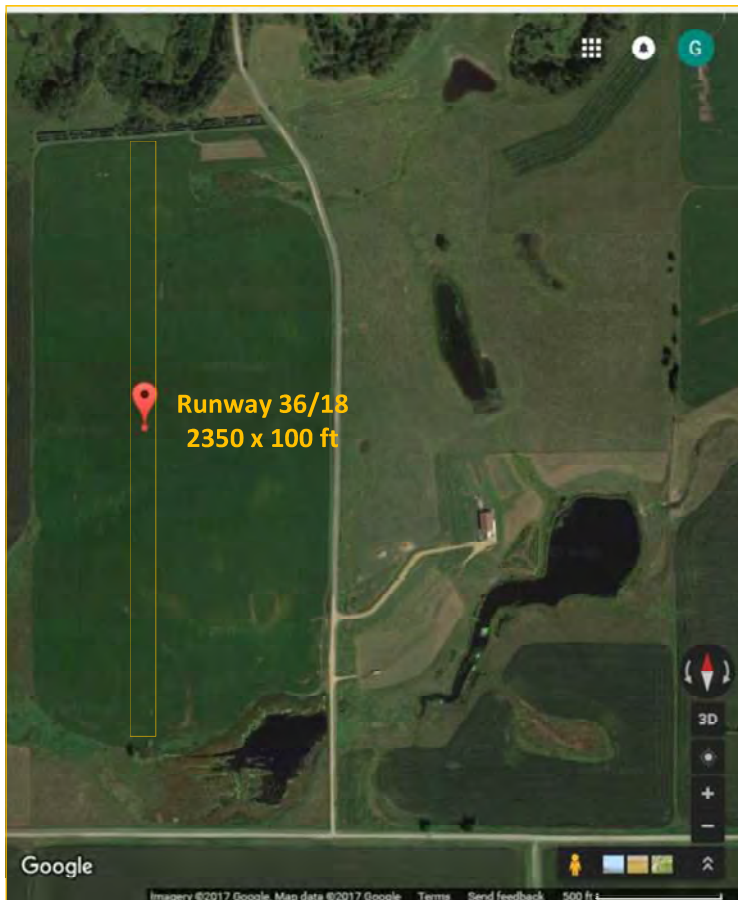


Figure 2 from My Public Comments



Attachment Sent to FAA During Airstrip Permitting Process

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WIND TURBINES REPRESENT POTENTIAL HAZARD TO PILOTS

March 26, 2009

By Ian J. Twombly

Wind turbines have the potential to be a hazard to air navigation, according to two new letters AOPA issued recently. While AOPA recognizes the role wind turbines play in green power generation, it is concerned that their tall construction could lead to potential collisions with aircraft and impact the reliability of radar.

AOPA made the comments in opposition to a bill in the Washington State legislature and on a request for comments to a wind farm proposed in Nantucket Sound off the coast of Massachusetts.

According to Greg Pecoraro, AOPA vice president of airports and state advocacy, "It has become increasingly important for AOPA to educate lawmakers across the country about the effects of these systems on aviation. Particularly so when the wind farms are in close proximity to airports," he said. "Aside from the obstruction itself, they can also interfere with communication and navigation, and wind patterns for all aircraft, especially gliders."

Pecoraro made the comments in his letter on Washington H.B.1008, a piece of legislation

that would regulate the installation and operation of wind turbines in the state.

"If the systems were to be installed near arrival or departure paths of these facilities, the safety of passengers and crew, as well as citizens below, would be severely compromised," Pecoraro said.

AOPA also is working on a high-profile wind farm issue off the other coast, in Nantucket Sound. This proposal caused political fireworks a few years ago when residents of the upscale islands opposed the clean energy source. Aesthetics aside, AOPA said there are serious aviation considerations as well.

Responding to the FAA's request for comments on the wind farm as a potential hazard to air navigation, AOPA said the proposed 130 wind turbines that cover a 35-square-mile area of the sound would cause a significant hazard to air navigation.

"The area of significant concern to AOPA is the high volume of low-altitude VFR flights between Barnstable Municipal, Martha's Vineyard, and Nantucket Memorial Airport," AOPA said.

The letter went on to say that the wind farm would impact radar coverage in the area, making it unlikely pilots would be able to receive flight following and other radar services over the water at lower altitudes.

The association will continue to monitor the wind turbine situation in Washington, Massachusetts, and around the country.

Ian J. Twombly

Ian J. Twombly is senior content producer for AOPA Media.

[GO TO IAN J. TWOMBLY'S PROFILE >](#)

From: Bernard Gervais bgervais@copanational.org 
Subject: SMS/COPA Report
Date: January 29, 2019 at 10:40 PM
To: garhoman@gmail.com
Cc: Kevin Elwood kelwood@copanational.org

BG

Mr. Horman,

Please feel free to use the SMS/COPA report for the purposes you see fit in the name of science and flight safety. If you could please cite the source when you mention material coming from it, it would be appreciated.

Best of luck!

Regards,

Bernard Gervais, ^{PMP}
Président - COPA - President & CEO
To advance, promote and preserve the Canadian freedom to fly
Faire progresser, promouvoir et préserver la liberté canadienne de voler.



Canadian Owners and Pilots Association
Association canadienne des pilotes et propriétaires d'aéronefs
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**BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA**

**IN THE MATTER OF THE
APPLICATION OF DEUEL HARVEST
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY**

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**STAFF’S FIRST SET OF DATA
REQUESTS TO INTERVENORS**

EL18-053

Below, please find Staff’s First Set of Data Requests to Intervenors. Please submit responses within 10 business days, or promptly contact Staff to discuss an alternative arrangement.

- 1-1) Provide copies of all data requests submitted to or by you and copies of all responses provided to those data requests. Provide this information to date and on an ongoing basis.
- 1-2) Refer to SDCL 49-41B-22.
 - a. Please specify particular aspect/s of the applicant's burden that you intend to personally testify on.
 - b. Please specify particular aspect/s of the applicant's burden of proof that you intend to call a witness to testify on.
- 1-3) Refer to SDCL 49-41B-25. Identify any “terms, conditions, or modifications of the construction, operation, or maintenance” that you would recommend the Commission order. Please provide support and explanation for any recommendations.
 - a. Specifically, what mitigation efforts would you like to see taken if this Project is constructed.
- 1-4) Please list with specificity the witnesses that you intend to call. Please include name, address, phone number, credentials and area of expertise.
- 1-5) Do you intend to take depositions? If so, of whom?

Dated this 12th day of February 2019.

Amanda M. Reiss

Amanda M. Reiss
Kristen Edwards
Staff Attorneys
South Dakota Public Utilities Commission
500 East Capitol Ave.
Pierre, SD 57501

Aviation Safety-risk Assessment of The Effect of Wind Turbines on General Aviation Aircraft

SMS Report No. 1101

Produced by



SMS Aviation Safety Inc.

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March 2011

CONFIDENTIAL

FOREWORD

This aviation safety-risk assessment was conducted to support decisions to manage the aviation safety-risks related to the effects of wind turbines on general aviation aircraft. The report contains information that may be proprietary. Recipients of the report are requested to restrict its circulation to those who are involved in decision making associated with wind farm development.

Please direct comments regarding this report to:

Terry Kelly, Managing Director
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EXECUTIVE SUMMARY

The recent growth of the wind energy industry across Canada caused the Canadian Owners and Pilots Association (COPA) to commission a multi-phased independent safety analysis of the effect of wind turbines on general aviation (GA) aircraft. The first phases of the study involved studying technical and operational literature to identify aviation hazards, so that a panel of subject matter experts from the aviation and wind energy industries could assess the associated safety-risks.

This report summarizes the results of the expert panel meeting held in Ottawa on February 10 – 11, 2011. It is intended to be used by government policy makers, wind farm developers and GA pilots to manage the aviation safety-risks associated with the interaction of GA aircraft with wind turbines.

The deliberations of the Expert Panel focussed on the physical hazards of wind turbine structures (i.e., wind turbines as obstacles to aircraft operating at low altitudes, and the potential effect of towers on ground-based navigation aids) and on the effects of the rotating blades of the wind turbines (i.e. turbine-induced turbulence, blade-tip vortices and wind shear).

The expert panel determined that the safety significance of wind turbines on the Canadian Civil Aviation System as a whole is very low. However, they collectively concluded that additional steps are necessary to further mitigate the risks faced by pilots flying GA aircraft. In particular, they determined that the risks to light and ultra-light aircraft operating in very close proximity to wind turbines during take-off and landings are from low to moderate significance. The panel concluded there was a strong need to better inform pilots, aviation and wind energy associations, and government and non-government policy makers on the potential risks to small aircraft caused by wind turbines. Furthermore, they concluded that the development and implementation of minimum setback distances around aerodromes would go a long way to reducing the safety risks to GA aircraft during take-off and landing.

To maximise the effectiveness of new mitigation strategies, the expert panel recommended that stakeholders from the wind energy and aviation industries – including regulatory bodies – better coordinate their activities. This will encourage the development of a systematic approach to wind farm development across Canada, which in turn will streamline the development process, minimize the number of challenges received by regulatory agencies and developers, and improve overall system safety.

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GLOSSARY

AGL	Above Ground Level
ASL	Above Sea Level
ATC	Air Traffic Control
CFS	Canada Flight Supplement / GPH205
COPA	Canadian Owners and Pilots Association
FL	Flight Level
ft.	foot
GA	General Aviation
IFR	Instrument Flight Rules
km	Kilometre
km/h	Kilometres per Hour
Kts	Knots (nautical miles per hour)
MEA	Minimum Enroute Altitude
mi	Mile
m/s	Metres per Second (where 1 m/s equals 3.6 km/h)
MOCA	Minimum Obstruction Clearance Altitude
MVMC	Marginal Visual Meteorological Conditions
MW	megawatts
NM	Nautical Mile (where 1 NM equals 1852 m)
TSR	Terminal Surveillance Radar
VFR	Visual Flight Rules
VOR	Very High Frequency Omnidirectional Range

1. INTRODUCTION

1.1 Background

Pressure to increase the amount of energy generated from alternative sources has led to a growing number of wind farms being constructed across Canada. This has increased the incidence of applications to construct wind turbines within close proximity to aerodromes, including certified aerodromes (airports).

In response, the Canadian Owners and Pilots Association (COPA), whose membership is made up of operators of privately owned general aviation (GA) aircraft and operators of many of the smaller aerodromes from which GA aircraft fly, has attempted to influence approval processes to ensure there are safe distances between wind turbines and existing aerodromes. COPA has achieved mixed success, in part because there has been no comprehensive safety-risk assessment of the effects of wind turbines on GA aircraft.

Consequently, COPA contracted SMS Aviation Safety Inc. to conduct an independent, third-party safety-risk assessment of the issue.

1.2 Purpose

The aim of the safety-risk assessment was to determine whether the risks of wind turbines to GA aircraft warrant a more systematic approach to safety-risk management.

1.3 Scope

The scope of the risk assessment was defined as the effect of wind turbines on general aviation (GA) aircraft¹.

1.4 Method

1.4.1 Overview

The risk assessment was conducted in three phases.

Phase One – Preliminary Hazard Analysis. The first phase involved the preparation of a hazard summary. This document was based on a study of the literature on the effects of wind turbines on the air, operational safety-risk assessments of wind turbines on Air Traffic Services, and texts on general fluid dynamics. The resulting document contained a preliminary list of hazards that can occur as a result of interactions between wind turbines and GA aircraft. The document was provided to the subject matter experts before they participated in the expert panel review.

Phase Two – Expert Panel Deliberations. The expert panel met in Ottawa, Ontario from February 10th to 11th, 2011. The panel was composed of persons with experience in the operation of GA aircraft and helicopters, air traffic control, airspace classification and structure, and the design and operation of wind-powered turbines. A list of the panel member and their affiliations is provided in Appendix A.

¹ A definition of GA aircraft is found in Section 1.4.3. Wind turbines are described in Section 1.4.4 and 2.1.

During the two-day session, the panel:

- received technical briefings related to wind turbines, GA and helicopter operations, and airfield impact assessment;
- used information from the briefings, the hazard summary and the risk assessment framework (described in Section 1.4.2 of this report) to identify the potential hazards and risks that could result from interactions between GA aircraft and wind turbines;
- drew on their experience and the available data to provide information for projecting the severity and likelihood of each risk;
- conducted a preliminary examination of the appropriateness of existing forms of mitigation to manage the aviation safety-risks; and
- discussed ways in which additional mitigation might better manage aviation safety-risks in the future.

Phase Three – Finalization of the Analysis. The analysis was finalised by integrating the information gleaned during the first two phases in a draft report. This report was then provided to the panel members for technical verification and comment. Following this review, the report was prepared in its final form.

1.4.2 Definitions and risk assessment categories

The following definitions were employed:

- Hazard: The condition or circumstance that can lead to loss of life or property.
- Risk: The consequence of a hazard, measured in terms of severity and likelihood.
- Mitigation: The measures taken or available to eradicate a hazard, or to reduce the likelihood or severity of a risk.

The categories outlined in Table 1.1 and Table 1.2 were employed in Section 3 to assess the risks resulting from each hazard.

Table 1.1: Risk Severity

Category	Definition	Description
A	Catastrophic	Destruction of property or loss of life
B	Major	Major damage and / or major personal injury
C	Minor	Minor damage and / or minor personal injury
D	Minimal	Inconvenience

Table 1.2: Risk Likelihood²

Level	Definition	Description
1	Occasional	Expected to occur, but not often
2	Seldom	Expected to occur infrequently
3	Remote	Slight chance that it might occur
4	Improbable	Not likely to occur
5	Extremely Improbable	Occurrence is almost inconceivable

1.4.3 Definition of General Aviation

General Aviation (GA) is one of two categories of civil aviation in Canada. The majority of the world's aircraft activity falls into the GA category. GA refers to all aircraft activity, both private and commercial, other than military and scheduled passenger and cargo flights. Some examples of GA are: private recreational flying and personal transportation, business aviation, flight training, air ambulance, police operations, aerial fire-fighting, air taxi, gliding, skydiving and non-scheduled commercial flights.

GA aircraft include gliders, powered parachutes, balloons, helicopters, ultralights, amateur-built (experimental) aircraft, certified piston aircraft and jet aircraft. Pilots flying GA aircraft have a variety of certifications, qualifications and experience.

For the purposes of this report, special operations, such as (non-military) search and rescue or police operations, were not considered to be part of GA; nor were balloon operations.

Even with these restrictions, the definition of GA is broad³. Consequently, the report attempts to identify as precisely as possible the specific areas of the GA system (aircraft types, pilots, operating environment, etc.) that can be affected by each hazard.

² All of the likelihood ratings are near the "infrequent" end of the frequency spectrum because aviation has earned an enviable record in which training, regulations and multiple layers of defence combine to reduce the likelihood of serious events occurring. By using finer ratings at this end of the spectrum, the expert panel was able to more precisely identify the likelihood of risks occurring, so that mitigation can be effectively targeted.

³ There were discrepancies noted regarding the definition of GA aircraft even amongst the expert panel. The definition provided by COPA was employed for this report.

1.4.4 Assumptions and Limitations of information and data

The risk assessment was completed using the following assumptions.

“Wind Turbines” were assumed to be of a type similar to those in general use across Canada. Specifically, it was assumed that they:

- are affixed to the ground with a solid structure, usually a tubular steel tower;
- have horizontal rotors of three blades;
- have maximum heights ranging from 120- 150 m (393 - 492 ft.) from ground to uppermost blade-tip⁴;
- have hub heights ranging from 80 - 100 m (262 - 328 ft.);
- have rotor diameters ranging from 80 - 100 m (262 - 328 ft.); and
- generate from 1500 – 3000 kW.

It was assumed that pilots operating GA aircraft adhere to the Canadian Aviation Regulations and Standards. However, the panel considered the risks that could arise as a result of such predictable circumstances as encountering reduced visibilities while en route.

It was assumed that GA flights are conducted in day and night conditions, and that GA pilots possess “average” skills and experience.

The impact of a wind turbine on a GA aircraft is not constant. For example, a stationary wind turbine does not disrupt airflow to the same extent as a rotating turbine. Consequently, it was assumed that turbines will rotate 80 % of the time.

Precise quantitative data regarding interactions between GA aircraft and wind turbines were for the most part not available. To determine the hazards of wind turbines, technical information regarding the effects of wind turbines on the surrounding air, and on ground-based air navigation equipment were identified. From this information, the SME panel extrapolated the magnitude and severity of the associated risks to GA aircraft.

It was determined that there was no need to examine the effects of wind turbines on air traffic control radar because the topic has been the subject of a number of recent reports⁵.

⁴ The vast majority of wind turbines in Canada presently fall within this range. Some countries are beginning to experiment with turbines of similar design but up to 200 m (656 ft.) tall.

⁵ For example: Safety Risk Assessment of Three Wind Farms on the Hamilton TSR, SMS Aviation Safety Inc., December 2010

1.5 Report Use and Format

The intent of this report is to inform policy makers, wind farm developers and GA pilots so that they can manage the aviation safety-risks associated with the interaction of GA aircraft with wind turbines.

Section 2 explains the details of the system that was assessed.

Section 3 contains the results of the risk assessment.

Section 4 describes the mitigation that could be applied to reduce the aviation safety-risks, if so desired.

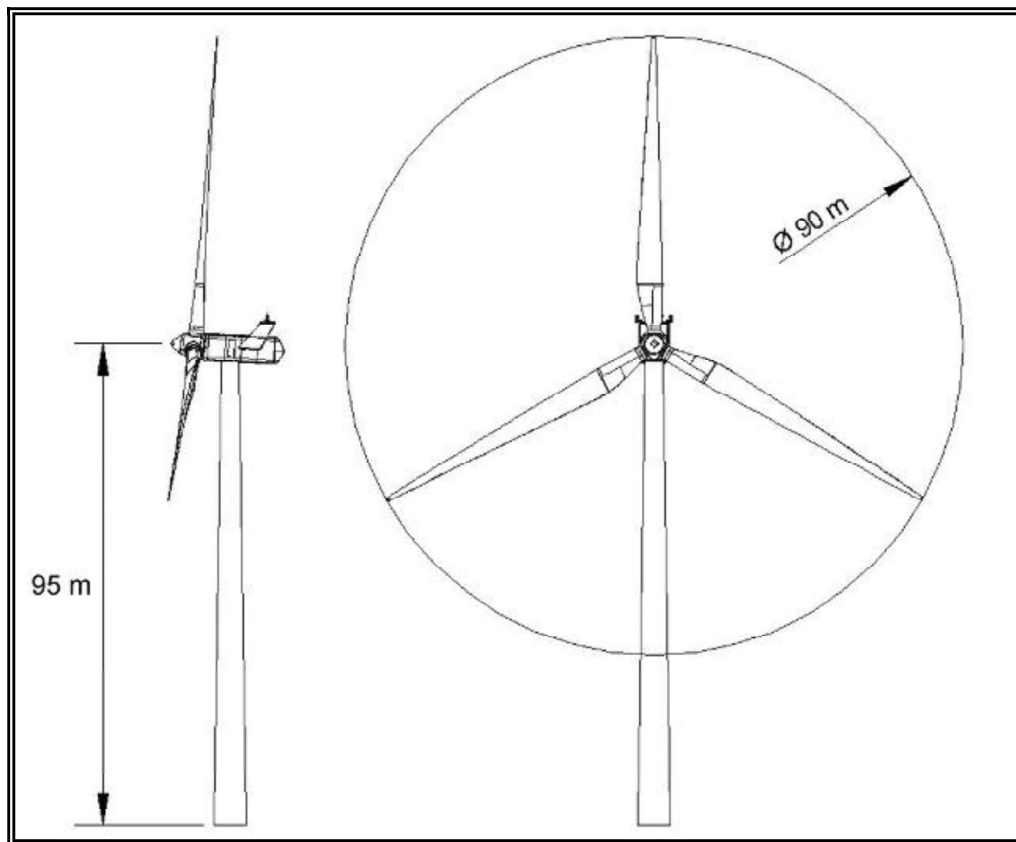
Section 5 provides conclusions regarding the longer-term forecast safety-risks of GA aircraft interactions with wind turbines in Canada.

2. DESCRIPTION OF THE SYSTEM UNDER REVIEW

2.1 Wind Turbines

The wind turbines considered in this assessment are those that conform to the common design currently employed across Canada for electricity generation, an example of which is shown in Figure 2.1. Wind turbines consist of a support tower, normally a tubular steel column, supporting an electrical generator. The generator is connected to the hub, which in turn is connected to three blades. The blades are primarily of composite construction. Depending on the model chosen, these composites can include combinations of lightweight carbon fibre, fibreglass and balsa wood in their makeup. Many turbines have variable pitch control mechanisms that alter the blades' angle of attack to extract maximum energy from the wind. Most turbine blades incorporate a metallic wire to provide grounding in the event of lightning strikes.

Figure 2.1 – Example of Typical Wind Turbine in Canada⁶



Wind turbines are normally equipped with wind vanes that identify wind direction and yaw-mechanisms that rotate the hubs upwind. The rotation of the blades is maintained at a nominal rotation rate, a rate controlled through the variable pitch mechanism and a brake.

Wind turbine blades do not turn all of the time, but instead start turning and generating electricity at wind speeds of approximately 5.8 Kts (11 km/h), and cut out (stop rotating) at wind speeds of approximately 48 Kts (90 km/h). The tips of wind turbine blades reach maximum speeds of around

⁶ Vestas V90 wind turbine, source: Vestas Wind Systems A/S.

320 km / h (173 Kts) – this speed is purposely restricted to minimize the noise generated by the blade tips.

Wind turbines are typically located in areas where there is sufficient wind to generate electricity at least 80% of the time. They are normally situated near an electrical grid with the capacity to carry the electricity generated. To minimize losses incurred in transporting electricity, wind turbines are generally located as near to consumers as possible.

The construction of a wind farm typically requires permits from a variety of Federal and Provincial Government agencies, and consultation with numerous stakeholders. For example, constructing a wind farm in Ontario typically requires 30 or more different permits from: the Federal Department of Fisheries and Oceans, Transport Canada, Environment Canada; the Ontario Provincial Ministry of Environment, Ministry of Natural Resources, Ministry of Transportation; Aboriginal People; and others. Transport Canada assesses a wind farm to determine whether the height and location of the proposed turbines will be obstructions to aviation. NAV CANADA assesses wind farm proposals that are submitted through the land use process for their potential effect on the air navigation system (navigation aids, surveillance equipment and communication infrastructure).

2.2 General Aviation in Canada⁷

In 2010, there were approximately 35,000 aircraft registered in Canada, of which approximately 27,000 were GA aircraft. More than 90 % of the total number of aircraft registered in Canada had gross take-off weights of less than 12,500 lbs.

There were roughly 38,000 pilots registered as “non-commercial pilots” in 2010 – pilots who are licensed to fly recreationally. There were nearly 25,000 pilots classified as “commercial pilots”. While these pilots are certified to fly commercially, a large portion of them do not fly professionally, and spend much of their flying time recreationally.

The Canadian Owners and Pilots Association (COPA) had approximately 17,500 members in 2010. Because their members make up a large percentage of all private pilots, COPA members can be considered representative of pilots who fly GA aircraft in Canada.

The average COPA member flies 30 hours each year⁸. For comparison, the average airline pilot in the U.S. flies an average of 75 hours per month⁹.

There are over 1800 certified and registered aerodromes in Canada¹⁰ as well as thousands of unregistered aerodromes¹¹. The majority of these are privately operated, registered or unregistered aerodromes. These aerodromes range from grass strips in farmer’s fields, to 3,500+ ft. paved runways. Most GA flights take-off and land at these private aerodromes. They are not regulated to the same degree as airports, and are generally not inspected by Transport Canada.

Because the range of operations included in the designation ‘GA’ is large, typical performance characteristics or operations are difficult to describe. Two categories of GA aircraft which make up a large portion of the total, and are more likely to interact with wind turbines, are described below.

The first is made up of small single engine airplanes that weigh under 3,500 lbs. Examples include Cessna 172, Piper Arrow, Beechcraft G36 and Cirrus SR22. These aircraft may be used in a variety of ways, including training pilots, flying recreational site seeing tours, flying supplies into remote

⁷ Section 1.4.3 contains a definition of aircraft that are considered to be GA aircraft for the purposes of this assessment.

⁸ Source: COPA.

⁹ Occupational Outlook Handbook, 2010-11 Edition, December 17, 2009.

¹⁰ Report: Transportation in Canada 2009.

¹¹ Source: COPA, 2011.

locations, etc. They usually cruise between 3,000 and 13,000 ft. (915 – 4000 m) above mean sea level (ASL) and are governed by visual flight rules (VFR) or instrument flight rules (IFR). They most often interact with wind turbines when taking-off and landing from aerodromes in the vicinity of wind farms, and when carrying out low-level operations such as aerial application (crop dusting).

The second group is ultralight aircraft. Ultralight aircraft are defined as having maximum take-off weights of 560 kg (1234 lbs.), maximum stall speeds of 39 Kts (72 km/h) at maximum take-off weight, and wing areas not less than 10 m² (107 ft.²). Ultralights are cost effective aircraft, and are typically flown by amateur pilots with less training and experience than those flying larger aircraft. Ultralights are flown under VFR, and because they are prohibited from certain classes of airspace, tend to fly closer to the ground, often at altitudes less than 5,000 ft. (1500 m) ASL. Ultralights are expected to interact with wind turbines during take-off, landing and cruise.

2.3 Helicopter Operations in Canada¹²

There were approximately 4,800 helicopter pilot licences in Canada in 2008¹³. Over 85 % of these licences were commercial. Unlike airplanes, most helicopters are commercially operated, due primarily to the expense of operating a helicopter.

Helicopters are typically flown close to the ground at typical altitudes ranging from 2,000 ft. to 100 ft. above ground level (AGL).

Helicopters can fly at speeds ranging from 0 Kts. (e.g. aerial photography) to 150 Kts. (e.g. air taxi). Average flight speeds are around 100 Kts (185 km/h).

Most helicopter operations are governed by VFR, but they frequently fly in sub-optimal weather conditions. Visual flight in conditions of 1 mi (1.6 km) flight visibility is not uncommon, and in abnormal circumstance, they may operate with as little as 0.5 mi (800 m) forward visibility. When encountering reduced visibilities, it is normal practice to fly low to the ground.

¹² The panel believed that the assessment of the effects on helicopter operations was essential because much of their flying takes place at low altitudes where they can interact with wind turbines.

¹³ Summary of Flight Crew and Air Traffic Control Licenses, Transport Canada, December 2008.

3. ASSESSMENT OF RISK

3.1 Introduction

The risk assessment team identified the hazards (conditions or circumstances that can lead to loss of life or property) associated with the interaction of GA aircraft and wind turbines; determined the risks (the consequences of each hazard, measured in terms of severity and likelihood); assessed the appropriateness of existing mitigation (measures that can be taken to eradicate hazards, or reduce the likelihood or severity of risks), and considered whether additional mitigation was required to address the identified risks.

The panel determined that the safety-risk posed by wind turbines to the totality of aircraft operations in the Canadian Civil Aviation System was low¹⁴. Only a very small portion of all aircraft movements in Canada are exposed to the effects of wind turbines.

GA aircraft are most exposed to wind turbines, resulting in increased safety-risk to this category of aircraft.

3.2 Hazards Related to the Interaction of GA Aircraft with Wind Turbines

Five system hazards related to the interaction of GA aircraft with wind turbines were identified. These included: physical obstacles to aircraft flying at low altitudes, wind turbine induced turbulence, wind turbine blade-tip vortices, wind turbine induced wind shear, and impact on navigation aids.

3.2.1 *Physical Obstacles to Aircraft Flying at Low Altitudes*

Wind turbines typically range from 120 - 150 m (394 - 492 ft.) in height above ground (AGL), and their blades cover an area ranging from 5,000 – 7,800 m² (54,000 - 84,000 ft²). Consequently, wind turbines are physical obstacles to low flying aircraft¹⁵.

Wind turbines are situated to take advantage of high average wind speeds. They are frequently sited along high terrain, or in fields where there are few barriers to wind flow. The airspace over the former is frequently used by pilots of small en-route aircraft, who can legally fly as low as 500 feet above the ground (and lower when landing or taking off). The latter is frequently used for aerodromes.

Additionally, wind farms are sited to take advantage of available electrical grid capacity. When possible, they are located near communities where the demand for energy is highest. This has the potential to conflict with airports and aerodromes that are also located close to communities. Consequently, it is not surprising that wind turbines and aerodromes can be in close proximity to each other.

Exposure to this hazard increases as the number and size of wind farms grow¹⁶. Exposure also increases as the size of wind turbines (i.e. the physical dimensions of individual turbines) increases. Recent technological advances are enabling wind turbines to be higher and larger, and this trend is

¹⁴ During the assessment, all of the identified risks to aviation as a whole in Canada were judged to be of "low significance" because they were assessed to fall under one of the following categories: A 5; B 4 – 5; C 3 - 5; or D 1 - 5.

¹⁵ A related hazard is meteorological towers, also known as met towers, used by the wind energy industry to obtain wind data prior to constructing wind turbines. These towers are fabricated of steel tubing and supported by guy wires, and can be up to 197 ft. (60 m) tall. Meteorological towers are typically unmarked.

¹⁶ Size of wind farm in this case means the number of wind turbines in a wind farm. Currently, wind farms in Canada range from a few wind turbines up to 70+ wind turbines.

likely to continue, since the amount of energy that can be extracted from the wind increases exponentially as the diameter of the wind turbine rotor increases.

Pilots are at greater risk of striking obstructions when the obstacles are difficult to see. This can occur in low ambient light conditions, or when flying VFR with low ceilings or visibilities (e.g. MVMC). In these circumstances, the risk is increased at locations where wind turbines are constructed near roadways that VFR pilots rely on for navigation.

The colour of wind turbines (usually grey / white) makes them difficult to identify in cloudy or snowy conditions. The relative position of the aircraft to the wind turbine and the horizon may make it difficult for the pilot to detect the obstacle. These conditions are further aggravated when the wind turbines are not depicted on air navigation charts¹⁷.

Aircraft are most exposed to wind turbines as obstacles when the wind turbines are located in areas where aircraft must fly at altitudes equal to or less than the maximum height of the turbines. This occurs most often when wind turbines are constructed near aerodromes.

Most GA aircraft (for example: Cessna 172s, ultralights, etc.) climb relatively slowly. These aircraft generally take an average of 2.5 km (1.6 mi) to climb to 500 ft. (152 m) AGL^{18,19}. Furthermore, aircraft on departure and approach are operated closer to their stall speed, limiting the manoeuvrability of the aircraft when avoiding obstacles. Finally, pilots face their highest cognitive demands (task difficulty, time pressure, etc.) during take-off and landing, reducing their ability to adequately deal with additional challenges, such as manoeuvring around obstacles²⁰.

Certain categories of GA flying such as aerial application (e.g. crop dusting), emergency medical service (EMS), ultralight flights, and float plane operations take place routinely at or below the height of typical wind turbines.

The consequences of an aircraft colliding with a wind turbine would be catastrophic (i.e., a category A loss). There have been no reported occurrences of aircraft striking wind turbines in Canada. The panel was aware of a fatal accident in which an aerial applicator in California collided with a meteorological tower that was gathering data for a wind farm²¹.

¹⁷ Although it is standard practice to depict wind farms on air navigation charts, it may be years before a chart is published within the revised information.

¹⁸ The panel noted that 500 ft. AGL is the standard height at which VFR pilots can safely begin a turn after departure. .

¹⁹ The distance to climb to 500 ft. AGL increases during the summer months when air is hotter and less dense.

²⁰ Loukopoulos et al, 2003.

²¹ National Transportation Safety Board report, Identification WPR11LA094, January 2011.

It was determined that without additional mitigation, the risks of relating to wind turbines as obstacles are:

- Aircraft collision with wind turbine components, with the likelihood judged to be improbable²² (A-4);
- Controlled Flight Into Terrain (CFIT) or Uncontrolled Flight Into Terrain (UCFIT) due to an avoidance manoeuvre near a wind turbine, judged to be either improbable or extremely improbable²³ (A-4/5);
- Pilot distraction due to efforts to judge proximity to wind farm, etc., judged to have a remote chance of occurring (D-3); and
- Extended flight route to avoid wind farms, judged to occur occasionally²⁴ (D-1).

Panel members examined the existing mitigation, which principally focuses on making pilots aware of the presence of turbines so they can avoid them. The panel concluded that this was inappropriate mitigation for aircraft on departure from or arrival at aerodromes.

Although there is existing regulation from Transport Canada regarding obstacle limitation surfaces around airports²⁵ to prevent the construction of tall structures, there is no regulation related to protective surfaces around registered or unregistered aerodromes.

Adding protection surfaces for aerodromes would enable GA aircraft to climb to a safe altitude before manoeuvring to avoid wind turbines. These protection surfaces would apply both to wind turbines being constructed near existing runways, and to new runways being constructed near existing wind turbines.

Additionally, the panel concluded there was a need to better inform the wind turbine industry on the risks of building turbines near aerodromes, and pilots about the risks of wind turbines.

Finally, to address wind turbines as obstacles to en-route GA aircraft, the panel believed there was a need to enhance the visibility of wind turbines. Although they did not have the technical expertise to discuss this in detail, they considered the feasibility of adding IR markings to make the turbines visible to special operations pilots flying with night vision goggles²⁶, and the possibility of enhancing lighting around the perimeter of wind farms.

The panel agreed that mitigation for this hazard would work best in combination (i.e. improved lighting + timely update of charts + education, etc.).

3.2.2 Wind Turbine Induced Turbulence

Electrical energy from a wind turbine is generated when the wind imparts a force on the turbine's blades, which in turn apply torque on a generator. The wind turbine blades impart an equal torque to the wind that passes over them, causing the air to become turbulent²⁷.

²² Highest likelihood if wind turbines are located near aerodromes, in bad weather conditions with poor visibility. Ultralights were felt to be at greater risk.

²³ This was judged to be more likely to occur in conditions of poor visibility. If manoeuvre took place during take-off or landing, aircraft designs that are particularly prone to stalling would be more exposed. If manoeuvre took place during cruise, faster aircraft were judged to be more exposed to this hazard.

²⁴ More likely to occur with aircraft that consistently operate at low altitude, in more heavily populated areas.

²⁵ TP312 – Aerodromes Standards and Recommended Practices, Transport Canada, March 2005.

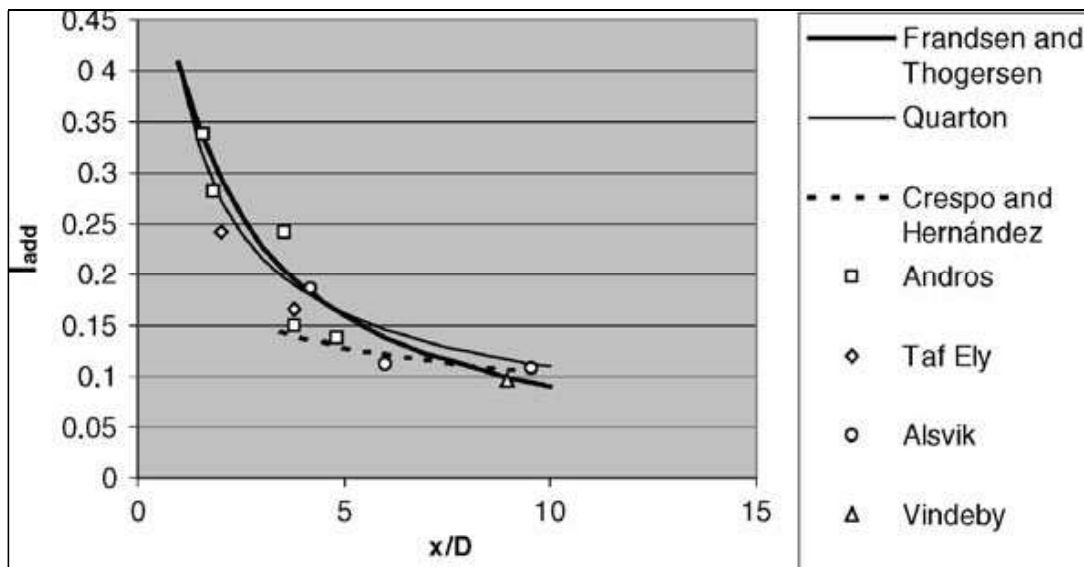
²⁶ Currently, flying with night vision goggles is not a common practice outside of military aviation.

²⁷ This comes from Newton's third law of motion: for every action, there is an equal and opposite reaction.

Studies have shown that the near-field wake turbulence behind a horizontal axis turbine extends up to ten rotor-diameters downstream from the turbine. As would be expected, the strength of the turbulence is stronger in the area immediately behind the wind rotor on the leeward side, and decreases in strength as distance from the rotor increases.

Figure 3.1 illustrates the results of one of these studies²⁸. It shows how the strength of turbulence behind a turbine compares to the strength of turbulence in the “free-stream” air (air flowing around the turbine but not coming into contact with the turbine). For example, from the diagram it can be seen that at five rotor diameters from the rotor ($x/D = 5$), the induced turbulence behind the wind turbine is expected to be approximately 15 %. This means that the induced wind speed fluctuations have a value of 15% of the average wind speed. Under normal conditions, wind contains between 10% and 15 % of ambient turbulence. The total turbulence behind a wind turbine is calculated from the contribution of ambient and induced turbulence, and is normally between 18 % and 21 % at five rotor diameters from the rotor ($x/D = 5$).

Figure 3.1 – Turbulence Strength as a Function of Distance from a Turbine Rotor



The spacing of wind turbines in a wind farm bears out this analysis. Turbulence reduces the amount of energy that a wind turbine can extract from the air. To maximise power production, turbine separation in a wind-farm is normally eight rotor diameters in the direction of the prevailing wind direction, and three to five diameters perpendicular to the prevailing conditions²⁹.

Turbulence is strongest on moderately windy days³⁰. Turbulence carries on further at times when the general air flow is less turbulent (for example, at night).

Aircraft will be exposed to turbine induced turbulence on the leeward side of the turbine within approximately seven rotor diameters of the turbine³¹. Exposure to turbulence would be greatest for

²⁸ Vermeer et al, 2003.

²⁹ Siting criteria is for 8 rotor diameters downwind, as a tighter spacing reduces energy production and decreases turbine operational life.

³⁰ Turbulence decreases in high winds due to the increased rotation speed of the rotor: with increased rotation speed, less torque is required to generate the same amount of electrical energy. Turbulence decreases as torque decreases.

³¹ The panel determined that turbulence would be a concern for pilots flying at a distance of up to approximately seven rotor diameters, after which pilots would experience the turbulence as little more than a bump.

small, light aircraft travelling at slow airspeeds and at the same height as the wind turbine rotor. This situation could occur when aircraft are landing or taking off from aerodromes with wind turbines in close proximity to the approach and departure paths. It could also occur to a pilot flying en-route who encounters deteriorating weather conditions, and is forced to fly at a low altitude to maintain visual contact with the ground and at slower speed to increase available reaction time for obstacle avoidance. Some aircraft, such as ultralights, cruise at low altitudes, and might be exposed to turbine induced turbulence more frequently.

Turbulence is not visible, so a pilot could inadvertently enter a turbulent zone if they were unaware of the presence of the turbines (e.g., in conditions of low light or visibility) or during take-off and landing at an aerodrome in close proximity to one or more turbines.

It was determined that without additional mitigation, the risks related to wind turbine generated turbulence are:

- Aircraft structural failure brought about by extreme forces applied to aircraft frame or control surfaces³², judged to be a remote chance of occurring (A-5)
- UCFIT due to loss of control after encountering wake turbulence, judged to be a remote chance of occurring³³ (A-4); and
- Temporary and non-sustained loss of control, judged to have a remote chance of occurring (D-3).

Because the strength of turbulence decreases as distance from the turbine increases, the risks to GA aircraft can be reduced by ensuring that there is sufficient distance between the turbine and the aircraft when the aircraft is at or below the height of the turbine rotor. For this reason, the mitigation for turbulence is similar to the mitigation for turbines as obstacles (3.2.1).

To reduce the risks to aircraft during the take-off and landing phases of flight, mitigation could include minimum setback distances for wind turbines from aerodromes. From the diagram shown in Figure 3.1, the panel determined that a distance of seven to ten rotor-diameters from any runway would be sufficient to reduce the risks related to turbulence to an acceptable level.

To reduce the risks to en-route aircraft, the panel believed the most appropriate mitigation to be pilot education. This would inform pilots about the risks related to turbulence caused by wind turbines, and how to judge safe distances from wind turbines. The panel agreed that to be effective, this mitigation would need to take several forms, including classroom training during flight schools, bulletins from Transport Canada, and newsletters from aviation industry groups.

Similar to the mitigation for turbines as obstacles, the panel agreed that mitigation for wind turbine induced turbulence would work best in combination (i.e. education + improved lighting + timely update of charts, etc.).

³² Ultralights and homebuilt aircraft are expected to be more susceptible to structural failure due to less stringent quality control measures during the manufacturing process for these types of aircraft.

³³ Helicopters could suffer this result due to hydraulic lock and subsequent loss of control, if the helicopter was hovering in the wake of a wind turbine.

3.2.3 Wind Turbine Blade-tip Vortices

Wind turbine blades produce vortices downwind from the turbine. Pilots are well aware of the hazard of *wing tip* vortices, as wing tip vortices generated by large aircraft have caused a number of well-publicized fatal accidents.

A wind turbine blade generates aerodynamic lift in the same way that an aircraft wing does, by creating a region of lower air pressure above it. Fluids flow from high to low pressure, so the pressure differential between the top and bottom of the turbine blade causes some of the air flowing below the wing to migrate toward the top of the wing via the wingtips. When air flows from below the wing and out around the tip to the top of the wing, it does so in a circular fashion, creating a vortex.

Vortices create additional drag on a wind turbine blade, called Lift Induced Drag. Vortices also create undesirable noise, leading wind turbine designers to purposely restrict blade rotation speed to keep noise at an acceptable level. Because they are noisy and inefficient, engineers try to reduce wing tip vortices to the greatest extent possible.

The strength of vortices created by a wing is heavily dependent on the shape of the wing and the force exerted by the wing on the air. Wings with high aspect ratios create weaker vortices, and thus are more efficient, than wings with low aspect ratios³⁴.

Table 3.1 shows the relative magnitude of vortex circulation resulting from wind turbine blades and from aircraft of various sizes. This table shows that the vortices caused by wind turbines are not strong enough to pose significant risk to GA aircraft.

Table 3.1 : Vortex Circulation Comparison³⁵

Example	Vortex Circulation
Cessna 172R	3.1
93m Turbine	5.4
Boeing 737	26.0
Boeing 747-400 (@ 156 Kts.)	83.0

The reasons that the relatively large “wing” used in wind turbines creates a relatively weak vortex are that they have very high aspect-ratios to maximize their efficiency, and because they exert relatively small forces on the air that passes over them³⁶.

Vortices probably do not exist past three rotor diameters outside of laboratory conditions. Figure 3.2 shows vortices created in a wind turbine in a wind tunnel experiment. This turbine is not removing energy from the wind, and hence is generating nearly no turbulence. In this instance, the vortices can be seen to extend for several rotor diameters behind the turbine. Figure 3.3 shows vortices emanating from the blade tips of a power-generating turbine in the atmosphere. In this case, it can be seen that the vortices exist for only a brief period immediately behind the rotor before they are destroyed by the turbulence created by the rotor.

Winds of high velocity will generate strong vortices. However, the vortices will be broken up more quickly by the higher wind speed, and by the turbulence that normally exists on windy days.

³⁴ An example of an airplane with a high-aspect ratio is a glider. These contrast with the wings of a CF-18 Hornet, have comparatively low aspect ratio.

³⁵ Ralph Holland, B Sc., Dip Ed., Dip. Com. Sc., ACT Australia. PowerPoint, n.t., Nov 2009. These numbers are based on a mathematical calculation related to such factors as: wing span, lift, speed, etc.

³⁶ Compared to the forces exerted on the air from a Boeing 747, for example.

Exposure to vortices is expected to be greatest for small, light aircraft travelling at slow airspeeds within very close proximity of a wind turbine (e.g., less than 3 rotor diameters). The panel concluded that the effect of the vortices will be insignificant in comparison to the risks related to the overall turbulence generated by the wind turbine.

Turbine blade tip vortices form a part of a system of air-disturbance on the leeward side of a wind turbine rotor. While it is difficult to measure accurately the size and strength of vortices, it is known that overall turbulence behind the rotor is much stronger than the strength of the vortices, and that vortices do not exist without turbulence under normal operating conditions. Thus, because vortices are a weak component of the turbulence of the rotor, the risks associated with vortices are subsumed under the discussion of risks related to turbulence in Section 3.2.2.

Because vortices are heavily dependent on wing design, there are technical forms of mitigation available to reduce their magnitude. For example, the panel was informed that some wind turbine manufacturers are examining the use of winglets on the end of turbine rotor blades, similar to those found on modern passenger airliners. Winglets reduce the strength of vortices, thus increasing the efficiency of the wings or turbine blades.

Because of the very low aviation safety-risks associated with turbine blade tip vortices to GA aircraft, the panel could not endorse these technical initiatives as mitigation.

Figure 3.2 – Vortices in a Wind Tunnel³⁷



³⁷ Source: Hand et al., NREL, 2002.

Figure 3.3 – Vortices from a Functioning Wind Turbine³⁸



3.2.4 Wind Shear Caused by Wind Turbines

Wind turbines reduce the wind speed in the air mass immediately downwind of the turbine, creating what is called in aviation, 'wind shear'.

Wind turbines convert wind energy into electrical energy. Energy in wind exists in several forms, including kinetic energy – the mass of the air moving with a certain velocity. Since the mass of air passing through a wind turbine does not change, and some energy is removed to create electricity, the velocity of the air is reduced³⁹. The reduction in wind speed behind a turbine is greatest when the turbine is extracting maximum power from the wind.

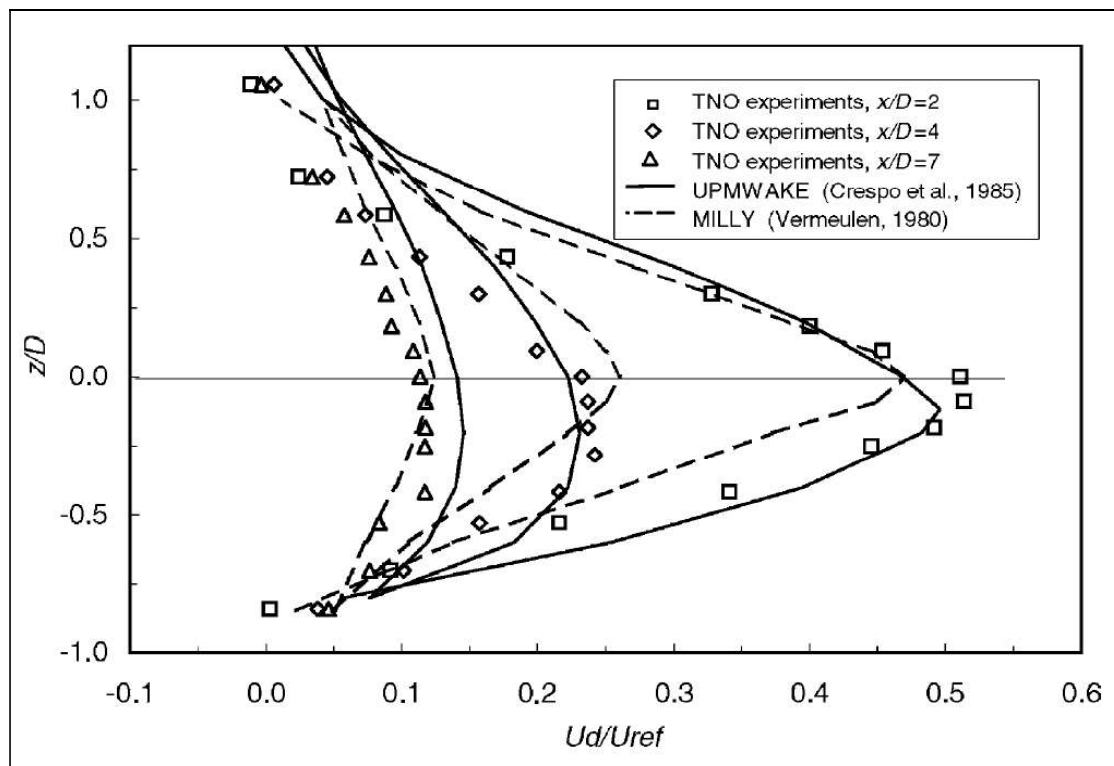
Because of their size, the stationary components of wind turbines can also reduce the downwind wind speed by obstructing wind flow. The steel pylon which supports the generator can be up to 100 m tall, and up to approximately 5 m in diameter at its base. The nacelle and generator assembly often weigh more than 95 tons.

Figure 3.2 depicts the magnitude of the decrease in wind speed as a factor of proximity to the turbine. The horizontal line (labelled 0.0) in the center of the chart equates to a line drawn horizontally through the hub of the turbine. The uppermost and lowermost horizontal lines (labelled 1.0 and -1.0, respectively) equate to the upper and lower reach of the turbine's blades. The decrease in wind speed increases as you move to the right along the horizontal center line. The different marker-shapes indicate different distances from the turbine rotor. For example, from the diagram it is shown that there is a 50 % reduction in wind speed at the middle of the turbine at a distance of 2 rotor diameters behind the rotor (square marker, $x/D = 2$). At a distance of 7 rotor diameters (triangular marker, $x/D = 7$), the reduction in wind speed at the center of the rotor is 10 %. At all distances, the reduction in wind speed near the tips of the rotor blades is nearly zero percent.

³⁸ Source: Technical University of Denmark, 2008.

³⁹ This is the result of the the first law of thermodynamics, also known as the law of conservation of energy, which states that energy cannot be created or destroyed.

Figure 3.2 - Wind Speed as a Function of Distance from Turbine Rotor⁴⁰



At high altitudes, pilots sometimes experience wind shear in the vicinity of the jet stream, causing an abrupt shaking of the aircraft. Pilots sometimes encounter wind shear on arrival or departure at some airports, when the wind changes abruptly in speed and direction (i.e., velocity) from a headwind to a tailwind. The panel determined that wind shear created by a wind turbine will feel more like the former. They came to this conclusion because behind a wind turbine, although the average speed of the wind may be lower than the free-stream air, pilots will experience only chaotic, turbulent air flow.

Aircraft will be most affected by wind shear if they are flown within three rotor diameters of the turbine rotor⁴¹. If a plane were "crabbing" (due to a crosswind) when it flew behind a wind turbine, the slower wind behind the turbine could, at least theoretically, cause the plane to change heading. This could cause concern to the unsuspecting pilot of an aircraft on final approach for a crosswind landing, or immediately after lift-off. The wind shear would be most severe in strong winds, which is also the time when a plane would be near its crosswind limits. It would be difficult for pilots to predict when and where they would experience the wind shear effects, because the area of wind shear changes as the wind turbines rotate to face into the wind.

⁴⁰ Source: Vermeer et al, 2003.

⁴¹ At further distances than this, pilots are expected to feel only turbulent air – the drop in wind speed will be indistinguishable from the general turbulence.

It was determined that without additional mitigation, the risks related to wind turbine generated wind shear are:

- UCFIT, which might occur to a pilot flying very near turbines at a speed close to the aircraft's minimum controllable speed⁴², which was judged to have a remote chance of occurring (A-4);
- Pilots being forced to change course and fly around wind farms to avoid the effects of wind shear, expected to occur occasionally (D-1); and
- Pilots being forced to divert from an unusable aerodrome, judged to have a remote chance of occurring (D-3).

Like turbulence, the strength of wind shear decreases as distance from the turbine increases. Thus the risks to GA aircraft can be reduced by ensuring that there is sufficient distance between the turbine and the aircraft when the aircraft is at or below the height of the turbine rotor. For this reason, the mitigation for wind turbine induced wind shear is similar to the mitigation for wind turbine induced turbulence.

For aircraft during take-off and landing, the panel concluded that the same seven to ten rotor diameter setback from runways used to mitigate turbulence would be adequate to mitigate the risks of wind shear. To reduce the risks to en-route aircraft, the panel believed the most appropriate mitigation to be pilot education on wind shear caused by wind turbines, and judging safe distances from wind turbines. .

3.2.5 *Interference with Signals generated by VOR Navigation Aids*

Wind turbines can cause multipath interference, which can result in out-of tolerance conditions for Very High Frequency Omnidirectional Range (VOR) navigation aids.

VORs communicate with aircraft using signals transmitted at frequencies in the official range of 108.10 to 117.95 MHz. Aircraft receive the signals, which are processed to identify the plane's bearing. Pilots use this information to navigate along an IFR airway.

Multipath interference is a phenomenon whereby a wave from a source (in this case, the VOR) travels to a detector via two or more paths. Because each of the paths is a different length, the components of the wave interfere when they are received.

Interference can occur to varying degrees when any tall object (a building, mountain, wind turbine, etc.) is located in close proximity to a VOR station. It is the tall steel tower that supports the wind turbine which causes the greatest impact on VOR signals. The number and size of the wind turbines, their construction (shape and construction material) and their proximity to the navigation aid will determine the degree of interference.

The quality of the signal from the VOR also impacts VOR performance. The performance of VOR facilities is variable, and some stations operate with minimal margin for disturbance. Others, like Doppler VOR stations, can tolerate more potential sources of interference without going out of specification.

Although VORs are installed, operated and certified for IFR navigation on published Airways, it is a well-known practice for VFR pilots to employ a VOR radial to aid them in navigating, particularly in remote locations. Pilots are more likely to rely on a VOR radial in deteriorating visibility, or while flying

⁴² It was judged that ultralights and smaller planes will be more susceptible to this effect. Pilots of ultralights also have less experience, less training, as a general rule.

in low ambient light conditions. Multipath interference might adversely affect the VOR radial being flown by the VFR pilot, causing the pilot to unknowingly wander from the intended flight path.

The panel judged the risks related to disruption of VOR signals to be:

- Collisions with obstacles (terrain in mountainous regions, or tall towers in western Canada, for example) due to being off course in conditions of marginal visibility, judged to be extremely improbable (A-5);
- Pilots becoming lost and their aircraft running out of fuel due to erroneous VOR signals in conditions of marginal visibility or locations with few landmarks, judged to be extremely improbable (A-5); and
- The imposition of non-preferred route structure by the air navigation service provider to avoid negative effects of wind turbines on VOR, judged to have a remote chance of occurring⁴³ (D-3).

One of the steps involved in the approval process prior to a new wind farm being constructed is an assessment of the effects of the proposed wind farm on NAV CANADA equipment, such as VORs and radar. In its evaluation, NAV CANADA identifies whether the proposed development is acceptable from their point of view, and identifies mitigation that can be taken to ensure that the effects of the development on NAV CANADA equipment are within an acceptable limit.

In Alberta, the provincial government will only authorize a wind farm proposal after NAV CANADA has confirmed that it will have no-effect on this equipment. Other provinces require that NAV CANADA assess wind farm proposals, but do not require that NAV CANADA approve proposals prior to authorizing them. Still other provinces do not include NAV CANADA in the government assessment process.

Terrain can play a role in reducing the effects that a wind farm has on a VOR. Hilly terrain between the navigation aid and the wind farm can reduce the magnitude of interference with VOR signals. Because turbine siting and construction can reduce the impact of wind turbines on VOR, the panel discussed educating developers on the effects that turbines can have on VOR, and on how to select and site turbines in ways that reduce the impact of their projects on VORs.

The panel felt that it was important to educate pilots that wind turbines may make VOR less accurate. This would further reinforce the existing rules around having alternative means of navigation.

3.3 Impact of Wind Turbines on Helicopters

Helicopters are exposed to most of the hazards listed in the previous section. However, helicopters are not affected in the same way or to the same extent as airplanes.

Since most helicopters operate between ground level and 2000 ft. AGL, wind turbines are obstacles that helicopter pilots regularly encounter. Because helicopter pilots have more flexibility in choosing the locations from which they take-off and land, turbines – as obstacles – pose less risk than they do for fixed-wing GA aircraft during these phases of flight. Because helicopters are more likely than GA aircraft⁴⁴ to cruise at altitudes which could cause them to encounter wind turbines en-route, wind turbines – as obstacles – pose more risk en-route than they do for fixed-wing aircraft.

⁴³ Panel members were aware that this has in fact occurred in some jurisdictions in the United States due to wind farms.

⁴⁴ Aerial applicators and ultralights are two examples of exceptions to this general rule.

Most low-level helicopter operations, during which helicopters may be expected to encounter wind turbines, take place when pilots encounter conditions of reduced visibility⁴⁵. In these instances, helicopter pilots reduce air speed (to between 0 and 60 Kts) so that they can see and avoid obstacles. While lower airspeed makes it easier for pilots to avoid obstacles, conditions of reduced visibility may make wind turbines (and in particular their rotating blades) more difficult for helicopter pilots to see.

The risks related to turbines as obstacles to low-flying helicopters are somewhat mitigated by the typical placement of wind farms. As discussed in Section 2.1, wind turbines are normally constructed close to the demand for electricity, or close to where there is grid capacity to transport the electricity. As such, wind farms are more likely to be constructed in densely populated regions of Canada. Because many helicopter operations take place in more remote areas and not in densely populated regions, their exposure to wind turbines as obstacles or turbulence generators will be reduced.

At cruise speeds, helicopters (i.e. rotary-wing aircraft) are not as susceptible to turbulence as airplanes (i.e., fixed-wing aircraft). Therefore, an encounter with wind turbine generated turbulence en-route will not pose as much risk. However, helicopters are particularly sensitive to turbulence when hovering, at which time the turbulence can cause a temporary loss of control.

Helicopters must hover when landing or taking off. Setback distances from helipads similar to those discussed in Section 3.2.2 for aerodromes would mitigate the negative effects of turbulence during these phases of flight. When landing at a site other than a prepared helipad, or planning an operation in which hovering is involved (e.g., long-lining), the panel believed that pilots should seek prior information on the location of wind turbines. In cases where helicopters are used to transport maintenance crews to and from wind turbines, consideration should be given to stopping turbine blade rotation while the helicopter is operating in the area.

3.4 Summary

The safety-risks associated with GA aircraft operating in very close proximity to wind turbines – in particular, light and ultra-light aircraft – during take-off and landings from aerodromes, are assessed to be from low to moderate significance. The remainder of the safety-risks to GA aircraft are assessed to be very low. The strategies to mitigate the hazards and risks are discussed more fully in Section 4.

⁴⁵ Reduced visibility in this case means visibility as low as 1 mile. In some instances, helicopter flying can be authorised in conditions with as little as 0.5 mile visibility.

4. MITIGATION

4.1 Introduction

As noted in Section 3, the significance of the safety-risks posed by wind turbines to GA aircraft is assessed to be very low, with the exception of light and ultralight aircraft operating from aerodromes, in which case the significance is assessed as low to moderate. The assessment takes account of current forms of mitigation, examples of which include:

- Lighting standards for tall structures published by Transport Canada⁴⁶;
- Standards in TP312 and TP1247E regarding minimum setback distances for tall objects from airports;
- Land development processes that enable the impact of proposed wind farm developments on NAV CANADA's air navigation services;
- Air navigation charts that show the locations of wind farms; and
- The Canadian Air Regulations (CARs) Part 602 which amongst other things presents the visual flight rules that govern most operations of GA aircraft (including minimum ceilings and flight visibilities).

The panel recognized that as the number of wind farms grows, GA aircraft will be increasingly exposed to wind turbines as hazards to aviation.

Section 4.2 describes additional mitigation that the expert panel considered necessary to address current hazards and risks. Section 5 discusses actions that can be taken to ensure that mitigation keeps pace with technological advancements in both the aviation and wind energy industries so that the associated risks can be maintained at an acceptable level.

4.2 Mitigation

4.2.1 Education Programs

Exposure to the aviation hazards of wind turbines can be reduced by improving knowledge of the associated risks. This concerted education program should target all participants of the system, and in particular pilots.

Many of the existing forms of mitigation aim to ensure pilots know the location of wind turbines. However, the panel felt strongly that the general understanding of pilots and wind developers of the effects of wind turbines on aircraft was low.

For new pilots, flight school curricula should be updated to teach the risks of flying near wind turbines. Topics could include technical descriptions of the hazards and risks of wind turbines, guidelines for flying near wind turbines, how to interpret wind farm lighting, warnings of particularly hazardous circumstances, etc⁴⁷. This training could be tailored to the risks related to the category of aircraft that the students are being trained to fly (e.g. light aircraft, ultralight aircraft, helicopters, etc.).

For current GA aircraft and helicopter pilots, similar information should be disseminated through a variety of channels. Such media could include Transport Canada aviation safety newsletters, videos

⁴⁶ Transport Canada is in the process of updating the requirements for marking and lighting wind turbines.

⁴⁷ Some of these topics may already be included in the curricula of some flight schools and colleges.

and safety posters, industry safety briefings, company-specific safety meetings and training sessions, association newsletters and a revision to the Canada Flight Supplement.

For wind developers, an industry awareness program on the effects of wind turbines on aircraft is warranted. The training could include the technical and safety effects of wind turbines on different components of the aviation system, and provide guidance on how to modify wind turbine siting, wind turbine selection, etc., to reduce aviation safety-risks.

4.2.2 Minimum Setback Distance Standards

As mentioned in Section 4.1, Transport Canada's TP312, *Aerodrome Standards and Recommended Practices*, defines the obstruction limitation surfaces around certified airports which restrict the building of tall structures near airports. These limitation surface standards do not apply to non-certified aerodromes, and there are no regulatory criteria that prevent wind farms from being developed in close proximity to either registered or non-registered aerodromes.

As discussed in Sections 3.2.1 through 3.2.4, GA aircraft are most exposed to risks relating to wind turbines when aircraft fly at or below the height of wind turbines – most often during take-off and landing.

The panel determined that to reduce the risk to GA aircraft when operating from non-certified aerodromes, an adapted form of obstacle limitation surfaces should exist. This could be achieved through regulatory standard or policy. Based on the available information, the panel determined that the following criteria would be appropriate:

- An area extending 2.5 km from both ends and at least one side of the aerodrome's runway in which there are no obstacles higher than 45 m⁴⁸;
- A restriction on constructing wind turbines within 7-10 rotor diameters from the approach surfaces⁴⁹; and
- The area of land under the aerodrome traffic pattern (or circuit) is free of wind turbines⁵⁰. Non-standard circuits can be specified to minimize turbulence based on the prevailing wind direction, among other factors⁵¹.

In some cases, the proposed setback distances would not be practical, for example, when wind turbines have already been constructed within 7 rotor diameters of a runway. In these situations, the panel felt that the risks associated with disrupted airflow due to wind turbines could be adequately mitigated through arrangements with wind farm operators to shut-down wind turbines in close proximity to the runways for specified periods. For example, this could be during particularly busy flying periods, such as Saturday mornings in the summer, or during scheduled flight school activities. While a possibility, the panel felt that this mitigation would likely be difficult to implement.

If formal legislation is not used to impose the above restrictions on wind farm development, the panel felt that the wind industry should be encouraged to update their already extensive consultation process to ensure that these topics are discussed with aerodrome operators who are potentially affected by proposed wind farm developments.

⁴⁸ 45 m is the height restriction used in TP312.

⁴⁹ A distance of 7-10 rotor diameters should be maintained from the approach surfaces and the runway. For example, this would mean that wind turbine construction should be restricted within 2.5 km *plus* 7-10 rotor diameters from each end of a runway.

⁵⁰ Circuits are specified in CARs Part 602. Circuits are normally left-hand (i.e. require left-turns when in the circuit). Registered aerodromes can specify in the Canada Flight Supplement that either left or right circuits are to be used.

⁵¹ To institute any non-standard circuit procedures (such as right hand traffic patterns or non-standard flight altitudes) the aerodrome must be registered with Transport Canada and approval must be sought from the Minister of Transport in accordance with Canadian Aviation Regulation 602.96 paragraph 3(C).

4.3 Special Operations

The panel noted that pilots carrying out special operations (e.g. police, search and rescue and military flights), are exposed to the effects of wind turbines, although the magnitude of this exposure is not known. The panel concluded that organizations involved in these operations would be responsible to take the necessary measures (e.g., develop standard operating procedures; specific safety campaigns, etc.) to mitigate the risks they expect to encounter.

Groups conducting special operations should be encouraged to review the findings of this report.

5. CONCLUSION AND OBSERVATIONS

5.1 Conclusion

It was determined that the safety significance of wind turbines on the Canadian Civil Aviation System as a whole is very low. However, the panel concluded that steps are necessary to further mitigate the risks faced by pilots flying GA aircraft. To maximise both the effectiveness of new mitigation strategies, they recommended that stakeholders from the wind energy and aviation industries – including regulatory bodies – coordinate their activities. This will encourage the development of a systematic approach to wind farm development across Canada, which in turn will streamline the development process, minimize the number of challenges received by both regulators and developers, and improve overall system safety.

5.2 Observations

5.2.1 General

The number of wind farms in Canada is expected to continue growing for the foreseeable future. Coupled with this growth are evolving technologies that enable wind farm developers to reach higher into the sky in order to capture the more constant wind found at increased elevations. In Europe, some developers have begun installing wind turbines similar to those described in Section 2.1 but reaching up to 200 m (656 ft.) in total height with rotors up to 136 m (442 ft.) in diameter. Newer technologies, such as helium-filled floating turbines suspended on 1000 ft. (305 m) cables⁵², could exacerbate existing hazards, or impose new ones, on low-flying aircraft.

To adequately address these new challenges, new technologies will need to be promptly identified by the regulators of the aviation system, and their impact assessed to ensure that mitigation will remain robust. For this to happen, strong ties are needed between the groups involved with the regulation of the aviation industry and groups developing wind farms and wind technologies.

Recent activities in this regard are working well. NAV CANADA and CanWEA are to be commended for their work in 2010 to build a link between their respective communities. The aim of the joint working group established between these two organizations aims to improve understanding of each industry. Such an approach builds trust and cooperation, which is critical when dealing with sensitive technologies and concerns of intellectual property. . Other stakeholders should be encouraged to take a similar approach.

5.2.2 Integration of the Wind Farm Approval Process

As discussed in Section 2.2, wind farm proposals go through an extensive and time consuming review process prior to being approved. Approval processes are not consistent across Canada, as most of the approvals are at a provincial or municipal level. The purpose of the multifaceted approvals process is to ensure that the many (and sometimes conflicting) interests of the public – environmental impact, economic stimulus, protection of health and safety, etc. - receive balanced consideration.

At the same time, there is pressure from many groups, including wind developers and provincial governments, to ensure that wind energy projects proceed. This pressure escalates as each step in the review process is successfully completed, because each step requires significant investment of resources, and project delays mean delays in investment in local economies. The downside of this

⁵² Source: Magenn.com

pressure is that it can encourage decision makers to ignore the concerns of potentially affected parties.

This situation establishes a potential system safety deficiency – conditions that permit hazards of a like nature to exist. The complexity of the approval processes and lack of integration across Canada makes it difficult to update requirements as the understanding of the effects of wind turbines evolve. Coupled with the pressure to complete wind projects, aviation safety hazards have the potential to go unidentified, and therefore unmitigated.

A national strategy is needed to address this situation. Common processes that influence local approval processes across Canada would benefit the growth of sustainable energy production. The longer that the current disjointed situation is allowed to persist, the more time and money will be lost on flawed projects, or on arguing for the approval of sound projects. Worse than that, the greater will be the chances of projects realizing safety, environmental or health risks due to lack of integration of new knowledge.

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APPENDIX A: RISK ASSESSMENT PANEL MEMBERS AND OBSERVERS

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Wind turbine wake aerodynamics

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Abstract

The aerodynamics of horizontal axis wind turbine wakes is studied. The contents is directed towards the physics of power extraction by wind turbines and reviews both the near and the far wake region. For the near wake, the survey is restricted to uniform, steady and parallel flow conditions, thereby excluding wind shear, wind speed and rotor setting changes and yawed conditions. The emphasis is put on measurements in controlled conditions. For the far wake, the survey focusses on both single turbines and wind farm effects, and the experimental and numerical work are reviewed; the main interest is to study how the far wake decays downstream, in order to estimate the effect produced in downstream turbines. The article is further restricted to horizontal axis wind turbines and excludes all other types of turbines.

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1. Introduction

The conversion of wind energy to useful energy involves two processes: the primary process of extracting kinetic energy from wind and conversion to mechanical energy at the rotor axis, and the secondary process of the conversion into useful energy (mostly electrical, but also mechanical for water pumps or chemical for water desalination or hydrolyses). This paper concerns the primary process: the extraction of kinetic energy from the wind. The major field of science involved in this process is aerodynamics, but it needs meteorology (wind description) as input, and system dynamics for the interaction with the structure. The latter is important since all movement of the rotor blades, including bending of the blades out of their plane of rotation, induces apparent velocities that can influence or even destabilize the energy conversion process. Aerodynamics is the oldest science in wind energy: in 1915, Lanchester [1] was the first to predict the maximum power output of an ideal wind turbine. A major break-through was achieved by Glauert [2], by formulating the blade

element momentum (BEM) method. This method, extended with many 'engineering rules' is still the basis for all rotor design codes. Recently, first results of complete Navier–Stokes calculations for the most simple wind turbine operational mode have been reported. Progress is significant in the 30-year history of modern wind energy. To name one example: a better understanding of the aerodynamics improved the efficiency of the primary process from 0.4 to 0.5 (out of a maximum of 0.592). Nevertheless, many phenomena are still not fully understood or quantified. This is due to several aspects that are unique for wind turbine aerodynamics:

- Although at present wind turbines are the biggest rotating machines on earth (up to 110 m diameter so each blade has approximately the size of the span of a Boeing 777) they operate in the lowest part of the earth boundary layer. Most aircraft try to fly high enough to avoid turbulence and extreme wind events, but for wind turbines steady wind is an off-design condition. All aerodynamic phenomena

are essentially unsteady, which, however, is still beyond the scope of current design knowledge.

- The very successful ‘Danish concept’ for wind turbines relies on stall for aerodynamic power limitation in high wind speeds: the increase in drag due to stall limits the torque produced at the rotor axis. All other aerodynamic objects (except military aircraft) avoid stall as much as possible because of the associated high loads and the possible loss of aerodynamic damping. Since many wind turbines rely on stall, a thorough understanding of unsteady (deep) stall is necessary.
- The flow in the blade tip- and root region is three-dimensional: for example, due to centrifugal and coriolis forces the flow in the boundary layer at the root is in spanwise direction, while the flow just outside the layer is chordwise. This effect delays stall, by which much higher lift is achieved compared to two-dimensional data. The relevance of two-dimensional data for wind turbine performance prediction is very limited.

The aerodynamic research for wind turbines has contributed significantly to the success of modern wind energy. For most unsolved problems, engineering rules have been developed and verified. All of these rules have a limited applicability, and the need to replace these rules by physical understanding and modelling is increasing. This is one of the reasons that the worldwide aerodynamic research on wind energy shows a shift towards a more fundamental approach. ‘Back to basics’, based on experiments in controlled conditions, is governing most research programs. This paper contributes to this by surveying all previous experiments and analyses on the flow through the rotor. For an overview on the technology development of wind turbines, see [3]. For a survey of the future R&D needs for wind energy, see [4].

2. Overview

Wind turbine wakes have been a topic of research from the early start of the renewed interest in wind energy utilisation in the late 1970s. From an outsider’s point of view, aerodynamics of wind turbines may seem quite simple. However, the description is complicated, by the fact that the inflow always is subject to stochastic wind fields and that, for machines that are not pitch-regulated, stall is an intrinsic part of the operational envelope. Indeed, in spite of the wind turbine being one of the oldest devices for exploiting the energy of the wind (after the sailing boat), some of the most basic aerodynamic mechanisms governing the power output are not yet fully understood.

When regarding wakes, a distinct division can be made into the near and far wake region. The near wake is taken as the area just behind the rotor, where the properties of the rotor can be discriminated, so approximately up to one rotor diameter downstream. Here, the presence of the rotor is apparent by the number of blades, blade aerodynamics, including stalled flow, 3-D effects and the tip vortices. The far wake is the region beyond the near wake, where the focus is put on the influence of wind turbines in farm situations, so modelling the actual rotor is less important. Here, the main attention is put on wake models, wake interference, turbulence models, and topographical effects. The near wake research is focussed on performance and the physical process of power extraction, while the far wake research is more focussed on the mutual influence when wind turbines are placed in clusters, like wind farms. Then, the incident flow over the affected turbines has a lower velocity and a higher turbulence intensity, that make the power production decrease and increase the unsteady loads. In the far wake the two main mechanisms determining flow conditions are convection and turbulent diffusion and in many situations a parabolic approximation is appropriate to treat this region. It is expected that sufficiently far downstream, the deleterious effects of momentum deficit and increased level of turbulence will vanish because of turbulent diffusion of the wake.

For the near wake, the survey is restricted to the uniform, steady and parallel flow conditions. Topics which will not be addressed, but which contribute to the complexity of the general subject, are: wind shear, rotor-tower interaction, yawed conditions, dynamic inflow, dynamic stall and aeroelastics, but these are not taken along in this article. Furthermore, the emphasis is put on measurements in controlled conditions. This is guided by the realisation that, although there have been attempts to tackle dynamic inflow and yawed related topics, the basics of wind turbine aerodynamics is not fully understood. For an overview of wind turbine rotor aerodynamics in general, see [5] and for an overview of unsteady wind turbine aerodynamic modelling, see [6].

Some field experiments are directed towards wake measurements, but changes in wind force and wind direction often obscure the effects of investigation. Most recent field measurement campaigns are related to the pressure distribution over the blade. These measurements are done as an international cooperation project as IEA Annex XVIII: “Enhanced Field Rotor Aerodynamic Database” see [7]. Because this topic is outside the scope of this article, the mention will be restricted to this and the focus will be on experiments under controlled conditions (i.e. in the wind tunnel).

For the far wake, the survey focusses on both single turbines and wind farm effects, which are modelled often in a different way. Both analytical and experimental

work is analysed. In the research work of the far wake frequent reference is made to the near wake behaviour, and consequently both are difficult to separate in a review paper; the main reason is that the near wake characteristics of the flow are initial conditions for the far wake. In the study of the far wake the effect of wind shear has to be retained, as it is an important mechanism to explain some phenomena of interest. The article is further restricted to horizontal axis wind turbines and excludes all other types of turbines. Nevertheless, sufficiently far downstream, the results for the far wake, could be extended to other turbines if the overall drag of the wind turbine that originates the wake is estimated correctly.

3. Near wake experiments

In sharp contrast to the helicopter research (see [8]), good near wake experiments are hard to find in wind energy research. And also, unlike in helicopter industry, there are only few financial resources available for experiments, but the need for experimental data is nevertheless well recognized (see also [9]).

Since the start of the wind energy revival, effort has been put into experiments, both for single turbines and wind farms. During the literature survey for this article, a number of references to wind tunnel experiments have been gathered, which are summarized in Table 1. These experiments on the near wake will be assessed by several criteria to evaluate the significance: model to tunnel area ratio, Reynolds number, completeness of acquired data. The properties to evaluate concern the feasibility to make a comparison between the experimental data and results from computational codes, so the fluid dynamics must be representable for validation. The suitable rotor properties thus are the aerofoil, the Reynolds number and the wind tunnel environment (specifically the tunnel to model area ratio).

The main focus will be on experiments in controlled conditions, because these are capable of providing the essential data for comparison with numerical simulations. The drawback of wind tunnel experiments is the effect of scaling on the representation of “real world” issues. On the other hand, the full-scale experiments (which are mostly field experiments) are put at a disadvantage by wind shear, turbulence, changing oncoming wind in both strength and direction on the exposure of physical phenomena.

Most experiments have been performed at rather low Reynolds numbers (as related to blade chord and rotational speed), only three cases with Reynolds numbers exceeding 300,000 are known [10–12]. Running a test at low Reynolds numbers shouldn't be much of a problem as long as an appropriate aerofoil section is chosen, of which the characteristics are known for that

particular Reynolds range. In this way, the model test does not resemble a full-scale turbine, but is still suitable for comparison and verification with numerical models. The same reasoning can be applied to the number of blades: although the current standard in wind turbine industry is to design three bladed wind turbines, experiments on two (or even one) bladed models can be very valuable.

Another aspect to consider is the model to tunnel area ratio. This is especially important for closed tunnels, but should also be taken into account for open-jet tunnels. Because of the mutual dependency of rotor inflow and wake structure, the performance of the rotor is influenced by the possibility of free expansion of the wake. As can be seen in the near wake experiments table, there are a great diversity of models and tunnels. The model to tunnel area ratio ranges from 1 to 125 (where the size of the model is apparently very small) to 1 to 1 (where it is clear that there cannot be any undisturbed expansion of the wake).

The most promising results are to be gained from wind tunnel experiments on full-scale rotors. However, these experiments tend to be very expensive, because of both investments in the model and the required tunnel size. There is only one known source: the NREL Unsteady Aerodynamic Experiment in the NASA-Ames wind tunnel (see [13,14]). In this case, the field test turbine of NREL, with a diameter of 10 m, was placed in the 24.4 m × 36.6 m (80 ft. × 120 ft.) NASA-Ames wind tunnel; the model to tunnel area ratio is 1 to 10.8 and the Reynolds number was 1,000,000. Although there was a considerable time to spend in the tunnel, most emphasis was put on pressure distributions over the blade and hardly any wake measurements were performed. Nevertheless, a considerable amount of data has been collected. This data will be the starting point for an international cooperation project as IEA Annex XX: “HAWT Aerodynamics and Models from Wind Tunnel Measurements” to analyse the NREL data to understand flow physics and to enhance aerodynamics subcomponent models.

Within the European Union, a similar project to the NREL experiment was started under the acronym “MEXICO” (model rotor experiments under controlled conditions). In this project, a three bladed rotor model of 4.5 m diameter will be tested in the DNW (Deutsch-Niederländische Windanlage: the German-Dutch Wind Tunnels) wind tunnel. For this experiment, the tunnel will be operated with an open test section of 9.5 m × 9.5 m; the model to tunnel area ratio is 1–3.8 and the Reynolds number will be 600,000 at 75% radius. One of the three rotor blades will be instrumented with pressure sensors at five radial locations. In the measurement campaign, also wake velocity measurements with PIV (particle image velocimetry) are planned. In this way, a correlation between the condition of the blade

Table 1

Descriptive name	TNO1	FFA	NLR	Cambridge	VTEC	MEL	TUDelft1	TUDelft2	TUDelft3	Rome
Institute or organization	TNO	FFA	NLR	University of Cambridge	Virginia Polytechnic Institute	MEL	Delft University of Technology	Delft University of Technology	Delft University of Technology	University of Rome
Country	Netherlands	Sweden	Netherlands	UK	USA	Japan	Netherlands	Netherlands	Netherlands	Italy
Leading person	P.E. Vermeulen	P.H. Alfredsson	O. de Vries	M.B. Anderson	M.A. Kotb	H. Matsumiya	L.J. Vermeer	L.J. Vermeer	L.J. Vermeer	G. Guj
Framework	National research programme	Basic research	National research programme	Ph.D.	Ph.D.	Basic research	Basic research	Basic research	Basic research	
Years	1978	1979–1981	1979	1982	~ 1983	1987	1985–1987	1987–1992	1983–2002	1991
Facility	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel
Size	2.65 m by 1.2 m	2.1 m by 1.5 m octogonal	3 m by 2 m	9.2 m by 6.5 m	1.82 m by 1.82 m (6 ft by 6 ft)	1.4 m by 1.4 m	2.24 m diameter	2.24 m diameter	2.24 m diameter	0.39 m diameter
Model to tunnel area ratio	1 to 31.2	1 to 56	1 to 13.6	1 to 8.46	1 to 16.3	1 to 3.9	1 to 125	1 to 3.5	1 to 3.5	1 to 1.9
Model size	0.36 m diameter	0.25 m diameter	0.75 m diameter	3 m diameter	0.508 m diameter	0.8 m diameter	0.2 m diameter	1.2 m diameter	1.2 m diameter	0.28 m diameter
Number of blades	2	2	2	2	3	2	2	2	2	1
Reynolds number range	25,000–50,000 at 50% R	65,000 at the tip, 60,000 at 75% R	350,000 at 75% R	335,000 at 75%R	?	# N/A	18,000 at the tip, 24,000 at 75% R	240,000 at the tip, 175,000 at 75% R	240,000 at the tip, 175,000 at 75%	45,000
Airfoil(s)	Gö 804	#N/A	NACA 0012	NACA 4412	Airplane propeller (Zinger 20-6)	NACA 4415	curved plates	NACA 0012	NACA 0012	NACA 0012
Chord	Constant	Tapered	Tapered	Tapered	Tapered	Tapered	Tapered	Constant	Constant	Constant
Tip chord	0.02 m	0.025 m	0.048 m	0	#N/A	0.04 m	0.0122 m	0.08 m	0.08 m	0.03 m
Pitch	constant	Twisted	Twisted	Twisted	Twisted	Twisted	Twisted	Twisted	Twisted	Constant
Design tip-speed ratio	7.5	3.5	8	10	3	6	5	6	6	5
Solidity	0.071	0.14	0.0674	0.047	?	0.11	0.08	0.059	0.059	0.068
Measurement techniques	pitot-tube, hot wires	hot wires	pitot- and static-pressure	Hot film, LDV	3-D yawhead probe	LDV	hot wires	hot wires	hot wires	hot wires
Availability of data			on microfiche in report				Yes, on request	Yes, on request	Yes, on request	
References	[34,35]	[16,17]	[10]	[11]	[36–38]	[52]	[21–23]	[15,56,57,24]	[61–64,28,24]	[58]
Type of work	CP, CT, averaged velocity data, turbulence intensities	CP, CT, averaged velocity data, flowviz, vortex spirals	CP, CT, averaged velocities	CP, CT, averaged velocities, detailed velocities	CP, averaged velocities	Detailed velocities	CP, CT, detailed velocities, flowviz	CP, CT, detailed velocities	Tip vortex properties, flowviz	Detailed velocities

Table 1 (continued)

Newcastle1	Newcastle2	Edinburgh	Herriot-Watt1	Herriot-Watt2	NREL	Mie	UIUC	Mexico	Descriptive name
University of Newcastle	University of Newcastle	University of Edinburgh	Herriot-Watt University	Herriot Watt University	NREL	Mie University	University of Illinois at Urbana-Champaign	ECN	Institute or organization
Australia	Australia	UK	UK	UK	USA	Japan	USA	Netherlands	Country
P.D. Clausen	P.R. Ebert	J. Whale	I. Grant	I. Grant	M. Hand	Y. Shimizu	C.J. Fisichella	H. Snel et. al.	Leading person
National research programme	Ph.D.	Ph.D.	Project	Project			Ph.D.	Project	Framework
1985–1988	~ 1992–1996	~ 1990–1996	~ 1996	~ 1996	1999	~ 2000	1997–2001	2000–2005	Years
Wind tunnel	Wind tunnel	Water tank	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Wind tunnel	Facility
0.26 m diameter	0.25 m diameter octagonal	400 mm by 750 mm	octagonal 1.24 m	2.13 m by 1.61 m	24.4 m by 36.6 m (80 ft×120 ft NASA Ames)	1.8 m diameter	1.52 m by 1.52 m	9.5 m by 9.5 m (DNW)	Size
1 to 1.0	1 to 1.0	1 to 12.5		1 to 4.4	1 to 10.8	1 to 1.7	1 to 2.9	1 to 3.8	Model to tunnel area ratio
0.26 m diameter	0.25 m diameter	0.175 m diameter	0.9 m diameter	1.0 m diameter	10.08 m diameter	1.4 m diameter	1.0 m diameter	4.5 m diameter	Model size
2	2	2	2 or 3	2	2	3	1, 2 or 3	3	Number of blades
210,000 at 75%R	255,000 at 75% R	6,400–16,000	?	?	1,000,000	325,000	?	600,000 at 75% R	Reynolds number range
NACA 4418	NACA 4418	flat plate	NACA 4611 to NACA 3712	NACA 4415	NREL S809	NACA 4415	Clark-Y	DU91-W2-250, RIS Ø A221, NACA 64-418	Airfoil(s)
Constant	Constant	Tapered	Tapered	# N/A	Tapered	Tapered	Constant	Tapered	Chord
0.058 m	0.06 m	0.01 m	# N/A	0.1 m	0.356 m	0.12	0.0457 m	0.085 m	Tip chord
Constant	Constant	Constant	Constant	# N/A	Twisted	Twisted	Twisted	Twisted	Pitch
4	4	6	6.7	# N/A	5	3	# N/A	6.5	Design tip-speed ratio
0.2	0.17	0.091	?	?	0.052	0.12	0.029, 0.058 or 0.087	0.085	Solidity
hot wires	hot wires	PIV	PIV	PIV, pressure taps	Pressure taps	LDV	Hot film	PIV	Measurement techniques
							As charts in thesis	After project finish	Availability of data
[53–55]	[46–50]	[40–42,44,45]	[65]	[65]	[13,14]	[12]	[51]		References
Detailed velocities	CP, detailed velocities	Detailed velocities, tip vortex properties	Tip vortex properties	Tip vortex properties	Flowviz	CP, detailed velocities, flowviz	CT, detailed velocities, tip vortex properties	CP, CT, detailed velocities, tip vortex properties	Type of work

circulation and the wake properties is expected to be achieved.

3.1. Global properties

The operational conditions of a wind turbine are described in a non-dimensional way with the C_P - λ and $C_{D_{ax}}$ - λ curves. The C_P - λ curve gives the power coefficient against the tip-speed ratio, where C_P is defined as the power from the wind turbine divided by the power available from the wind through the rotor area, so $C_P = P / \frac{1}{2} \rho V_0^3 \pi R^2$ and λ is the rotor tip speed divided by the oncoming wind speed, so $\lambda = \omega R / V_0$ (similar to the reciprocal of the advance ratio in helicopter terminology). The $C_{D_{ax}}$ - λ curves gives the axial force coefficient against the tip-speed ratio, where $C_{D_{ax}}$ is defined as the axial force on the total rotor divided by the reference value, so $C_{D_{ax}} = D_{ax} / \frac{1}{2} \rho V_0^2 \pi R^2$.

A lot of the references do give data for the global properties of the rotor, but only for the configuration parameters of the tests. Good practice would be to thoroughly test the rotor before trying to experiment on the wake, providing a proper documentation of the rotor for later analysis. The curves given by de Vries [10] (see Fig. 1) and Vermeer [15] (see Figs. 2 and 3) show typical examples for two different rotor models.

3.2. Flow visualisations

Flow visualisation can give information, mostly qualitative, about the flow in the vicinity of the rotor and can reveal areas of attention. It can be done either in the wake, trying to reveal rotor related flow patterns, or on the blade, trying to reveal blade related flow pattern.

One of the first flow visualisation experiments is done at FFA by Alfredsson [16,17]. Later by Anderson [11], Savino [18], Anderson [19], Eggleston [20], Vermeer [21–23] and [24], Hand [13] and Shimizu [12].

There is a distinction between two types of flow visualisation with smoke: either the smoke can be inserted into the flow from an external nozzle, so the smoke is being transported with inflow velocity and shows the cross section of the tip vortices (see Figs. 4–6), or the smoke is ejected from the model (mostly near the tip), so the smoke trails are being transported with the local velocity and show a helix trace (see Fig. 7).

The FFA experiment by Alfredsson was originally set out for wind farm effects, but was used later on for deducing parameters for a single wake. In Fig. 4, as much as six tip vortex cores can be counted, so for this two-bladed rotor this means three full revolutions. The visibility of these vortex cores is dependent on several aspects: the quality of the wind tunnel with respect to turbulence intensity, the quality of the smoke and illumination, but also on the strength of the tip vortex itself.

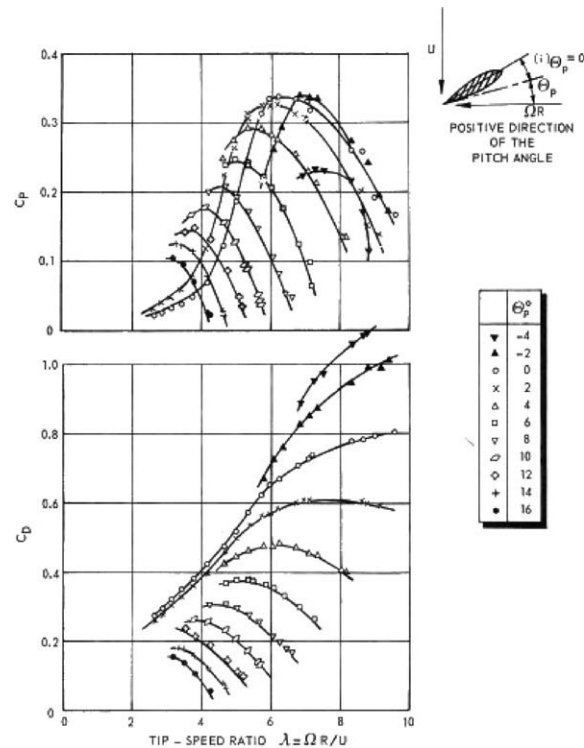


Fig. 1. Influence of pitch angle, θ_{tip} , on power coefficient (top) and rotor drag coefficient (bottom) versus tip-speed ratio λ (from [10]).

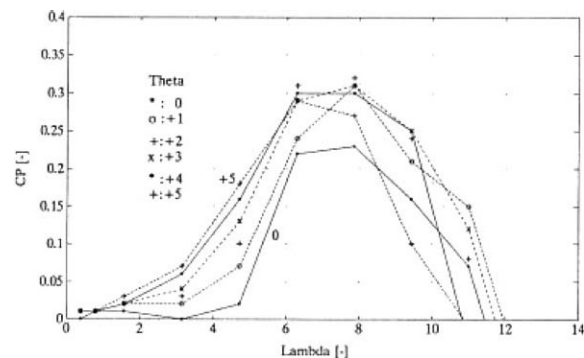


Fig. 2. Power coefficient as function of tip-speed ratio, λ , with tip pitch angle, θ , as a parameter (from [15]).

Also at TUDelft, similar smoke pictures were taken by Vermeer [24] (see Fig. 6). Compared to the FFA pictures, these appear rather poor, which might be due to the turbulence level and the quality of the smoke nozzle. Although the rotor model is really small (0.2 m diameter), it has been used in the first phase of a long-term wake research programme. With this model, the initial measurements have been carried out and some interesting observations have been made: when setting

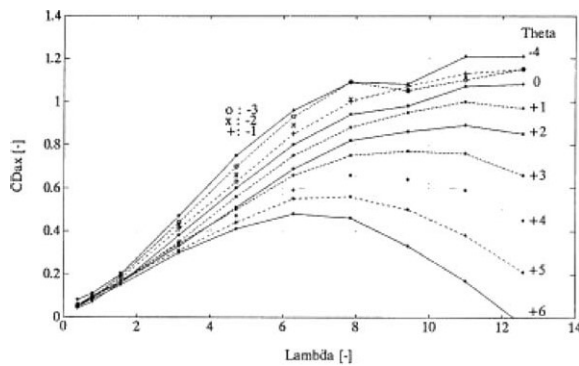


Fig. 3. Axial force coefficient as function of tip-speed ratio, λ , with tip pitch angle, θ , as a parameter (from [15]).



Fig. 4. Flow visualisation with smoke, revealing the tip vortices (from [16]).

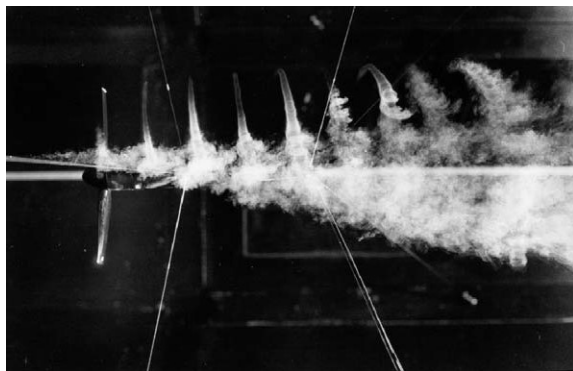


Fig. 5. Flow visualisation with smoke, revealing smoke trails being 'sucked' into the vortex spirals (from [16]).

the two blades at different pitch angles, the two tip vortex spirals appear to have each their own path and transport velocity. After a few revolutions, one tip vortex catches up with the other and the two spirals



Fig. 6. Flow visualisation experiment at TUDelft, showing two revolutions of tip vortices for a two-bladed rotor (from [24]).



Fig. 7. Flow visualisation with smoke grenade in tip, revealing smoke trails for the NREL turbine in the NASA-Ames wind tunnel (from Hand [13]).

become entwined into one. Unluckily, there are no recordings of this phenomena.

During the full scale experiment of NREL at the NASA-Ames wind tunnel, also flow visualisation were performed with smoke emanated from the tip (see Fig. 7). With this kind of smoke trails, it is not clear whether the smoke trail reveals the path of the tip vortex or some streamline in the tip region. Also, these experiments have been performed at very low thrust values, so there is hardly any wake expansion.

A different set-up to visually reveal some properties of the wake was utilised by Shimizu [12] with a tufts screen (see Fig. 8).

Visualisation of the flow pattern over the blade is mostly done with tufts. This is a well-known technique and applied to both indoor and field experiments (see [16–20,25–27]), however since blade aerodynamics is

a related subject, but beyond the scope of this article, only one mention will be made of such an application.

Vermeer [28] has tried to correlate the flow pattern visualised by tufts on the blade with near wake velocity patterns, in order to get a better understanding of how to interpret velocity signals. Especially, the location of stall on the blade was the focus of this experiment. The hot-wire probe was located at 65% radius and recorded velocity traces over ten revolutions. There appeared to be a great difference between attached flow (Fig. 9) and stalled flow (Fig. 10). In attached flow, the velocity changes associated with the blade passages (at 90° and 270° azimuth angle) are steady and the regions associated with the remains of the boundary layer (just after 0° and 180° azimuth angle) are relatively small, in contrast to stalled flow, where the blade passages cause changing magnitude (because of fluctuating circulation) and the remains of the boundary layer is wide and dominated by erratic fluctuations.

A novel technique of blade flow visualisation has been devised by Corten [29–32] in the form of what he has entitled stall-flags. The operational principle of the stall-flags is shown in Figs. 11 and 12. The stall-flag basically consists of a hinged flap and a retroreflector, fitted on a sticker. These stickers have such a size that a few hundred can be positioned on a full-scale rotor blade. When the flow over the rotor blade is non-stalled, the flap covers the reflector, where-as in stalled conditions, the reflector will be uncovered.

Stall flags are suitable of surveying the stall behaviour of full scale wind turbines on location. By installing a powerful lightsource in the field (up to 500 m downstream of the turbine), the whole rotor area can be illuminated, revealing all visible reflectors (see Fig. 13). The stalling behaviour is recorded by a digital video camera. Subsequently, the video frames are fed into the computer, which can analyse automatically thousands of frames, thanks to the binary character of the stall flag

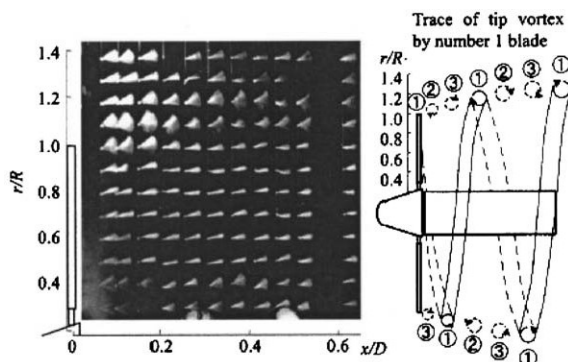


Fig. 8. Flow visualisation by tufted grid method (from Shimizu [12]).

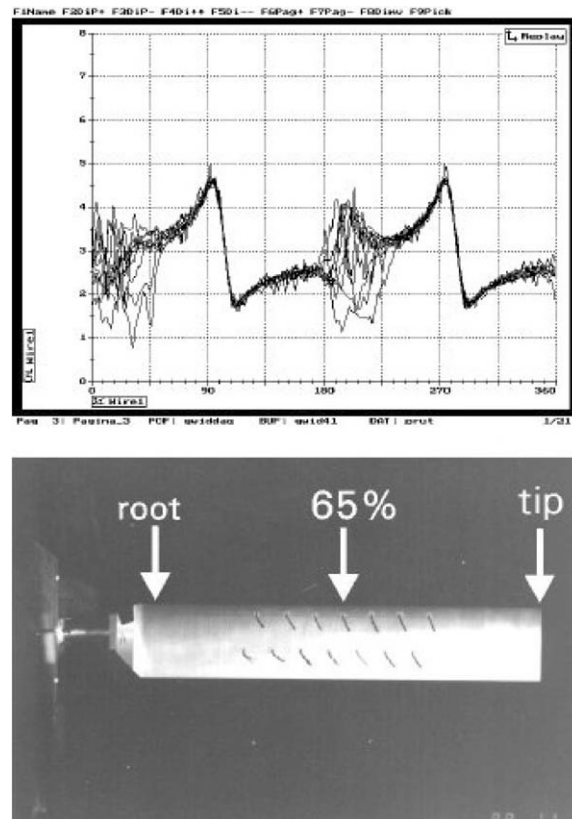


Fig. 9. Correlation between flow condition on the blade and observed velocity pattern in the near wake for non-stalled conditions (from [28]). The blade passages, recorded at 90° and 270° rotor azimuth angle, are steady.

signal. Statistical properties of the very dynamic process of stalling can be derived, so that one can determine whether the behaviour meets the design. If deviations are notified, it can be derived from the data which precise adaptations have to be made. The adaptations are made by applying vortex generators or stall strips or by pitching the blades slightly. Therefore the stall flag technique can be seen as a diagnostic tool, which also can prescribe the cure. An example of such diagnostics was the analysis of the double stall problem, see [32].

As easy as it is to visualise the tip vortex, so hard it is to do the same for the root vortex. Vermeer has tried to visualise the root vortex of the TUDelft rotor model (see [33]). In a total length of half an hour video material (at 25 frames/s), it is possible to locate a few frames on which a clear root vortex is visible. This has several causes: the root vortex is weaker than the tip vortex, the attachment of the root of the blade to the hub and the hub itself prevents a distinct vortex to be formed. As it is hard to visualise the root vortex, getting experimental data will be extremely difficult. This is regrettable,

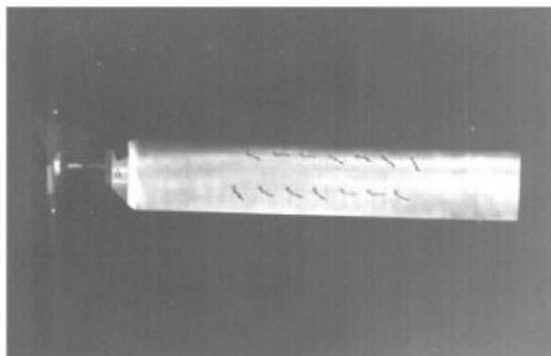
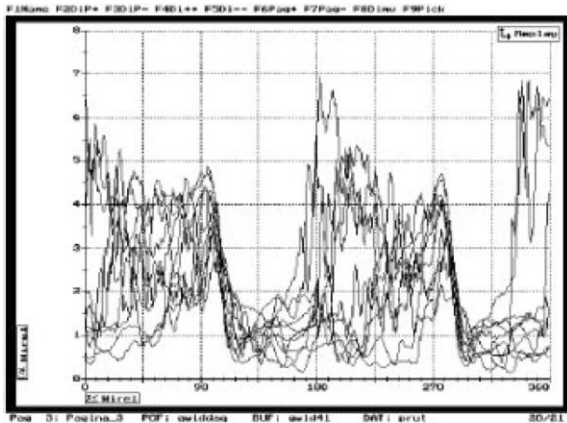


Fig. 10. Correlation between flow condition on the blade on observed velocity pattern in the near wake for stalled conditions (from [28]). The blade passages, recorded at 90° and 270° rotor azimuth angle, show changing magnitude.

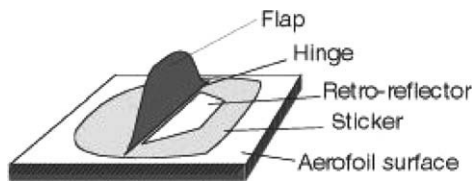


Fig. 11. The stall flag, consisting of a hinged flap and a reflector (from [32], © Nature, with permission).

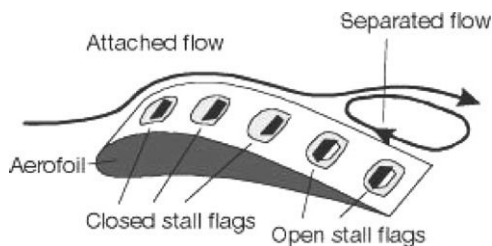


Fig. 12. Stall flags, showing the separated-flow area on an aerofoil (from [32], © Nature, with permission).



Fig. 13. Recording of stall-flag signals from the NEG Micon turbine in California (from [32], © Nature, with permission).

because calculations have shown that including or excluding the root vortex does make a lot of difference, especially under yawed conditions.

3.3. Averaged data

Averaged data dealing with velocity distribution in the wake is mostly used for attempts to analyse power and thrust, which are the global properties of a wind turbine, and do not reveal much about the physical process of power extraction. The experiments have mostly been carried out in the early years of wind turbine research (up until 1983), with modest equipment (Pitot tubes and pressure sensors), see [10,16,17,34–38]. Most data are shown at radius scale, including the rotor model axis area, e.g. see Fig. 14. This is rather directed towards wind farm research, but clearly shows the path towards near wake research in which detailed data is related to its spanwise location.

Wind profiles are also measured in non-uniform flowfields (see [36] and Fig. 15) and even in atmospheric boundary layers (see [39]).

3.4. Detailed data

Detailed wake data is acquired to provide a better understanding of the underlying physics of wind turbine aerodynamics. The experiments with detailed data are done after 1982, when more sophisticated equipment was employed. This section will be divided into two parts, one concerning velocity measurements and one concerning tip vortex properties. The experimental equipment has changed to fast response pressure sensors, hot wires (HW), laser doppler (LDV) and as a latest promising development particle image velocimetry

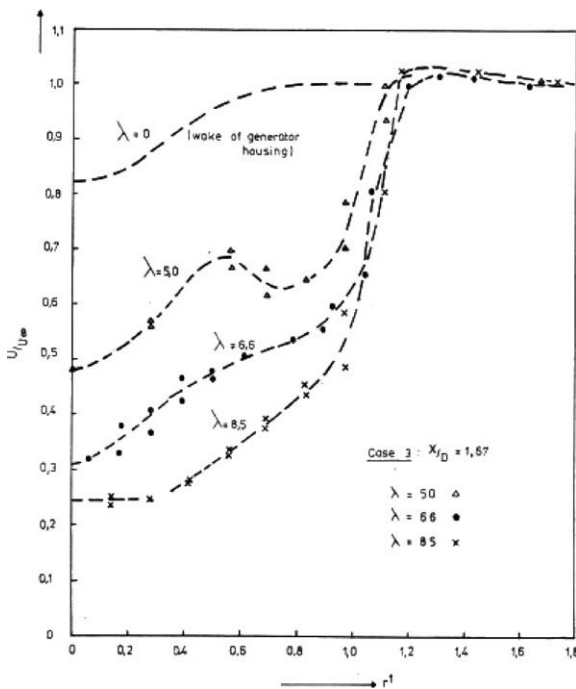


Fig. 14. Cross wind profiles, showing the velocity deficit, as a function of radial distance, with the tip-speed ratio as a parameter, for axial distance $x/D = 1.67$ (from [34]).

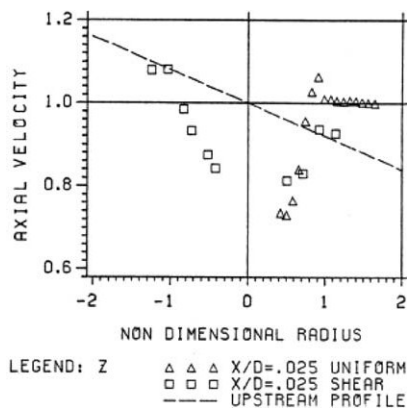


Fig. 15. Axial velocity profiles, showing the velocity deficit, at axial distance $X/D = 0.025$, for both uniform and shear flowcases together with the upstream shear profile (from [36]).

(PIV). Only a few elaborate studies are known [24,40–51]. The rest seems incidental experiments.

The study from Whale was one of the first to apply PIV to wind turbine wakes. In his case, this was done in a water tank. The major drawback here was the Reynolds number, which was very low (from 6400 to 16,000). Despite of this disadvantage, this study

comprises both experiments and analysis by an advanced vortex lattice method.

The study from Ebert is very elaborate and has put a strong accent on the repeatability of the data (many runs were re-done when strict criteria on e.g. wind tunnel velocity steadiness over a run were not met), but suffers from a major drawback: the diameter of the rotor model is the same as the “diameter” of the octagonal tunnel.

In Fisichella’s case, a lot of experimental data is acquired (and reported) for a rotor operated in 1, 2 or 3 bladed mode. Also, flow visualisation was done, but mostly at off-design conditions (low and high tip-speed ratios). Although the thesis of Fisichella gives a thorough overview of the research area, the analysis part is a little underexposed in his thesis.

The most comprehensive study has been carried out by Vermeer (for an overview, see [24]). The study started with measuring the global parameters of the rotor model and then advanced to cover many topics related to the near wake: detailed wake velocities, wake expansion, tip vortex strength and tip vortex propagation speed. Although the measurement sessions date from the early 1990s, there is still a lot of data-mining to be done (see next section).

3.4.1. Velocities

Detailed velocity measurements have been performed at numerous places with numerous different models in the same number of different tunnels [11,15,40–58]. Most important finding in the detailed velocity measurements in the near wake is the revelation of the passage of the rotor blades. This is shown by Tsutsui [52] with LDV (even in the rotor plane) (see Fig. 16), by Guj [58] upwind of a single blade turbine (see Fig. 17), by Ebert [48] (see Fig. 18), Fisichella [51] and by Vermeer [57,24] (see Fig. 19).

Especially at TUDelft, a lot of work has been done on trying to calculate the local bound vorticity on the blade from this very distinct velocity pattern (see [57]), but also in some other references, a comparison is made between experimental data and various calculational methods. In all comparison, attempts are made to find the match between the fluctuation related to the blade passage with the circulation as close as possible. But a recent study has shown that this approach does not give a good estimation for the bound circulation (see [59]). During this study, an analysis model, as opposed to a prediction model, was developed. This model is based upon the vortex line method (and Biot–Savart’s law) and ‘fed’ with as many experimental data as present. The vortex distribution over the blade in radial direction is represented by a set of orthogonal functions. By using the wake geometry, as deduced from the measurements, a set of equations can be build to express the wake velocities. Because the wake velocities are measured at several axial and radial positions and sampled at 0.5°

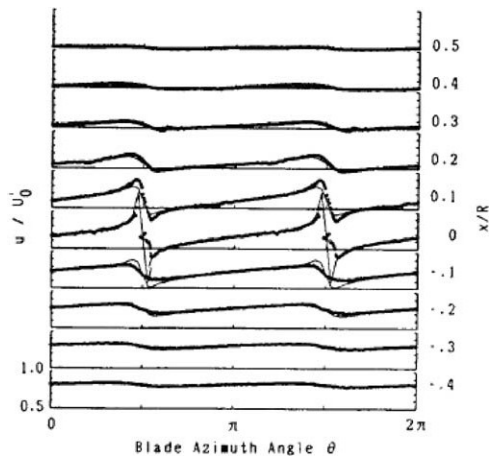


Fig. 16. Axial velocity component (at $r/R = 0.7$) as a function of rotor azimuth angle for several axial distances, both upstream and downstream of the rotor (from [52]). Blade passages are shown at $\frac{1}{2}\pi$ and $\frac{3}{2}\pi$ blade azimuth angle.

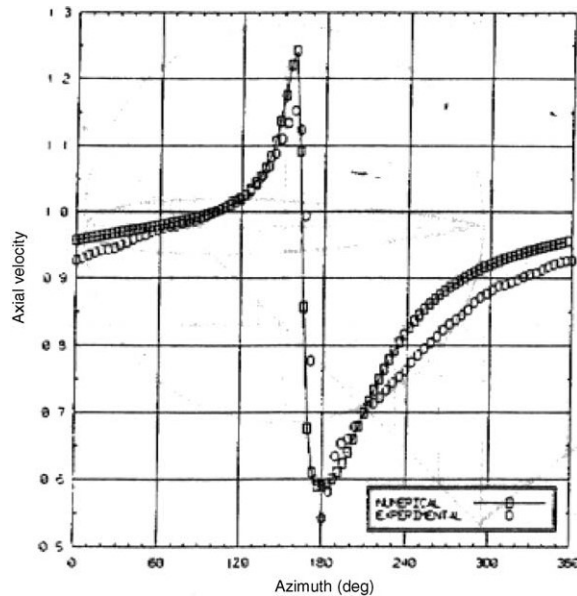


Fig. 17. Axial velocity in near wake, showing blade passage at 180° , as a function of rotor azimuth angle, for a single bladed rotor model (from [58]).

azimuth angle, a highly overdetermined set of equations is derived. By solving these equations with a least squares method, the bound circulation can be calculated, and from this distribution the wake velocities can be compared with the measured ones (see Fig. 20).

One of the major findings was that the velocity fluctuation caused by the blade passages can only partially be attributed to the bound vorticity on the blade, but when the measurement position is close to the

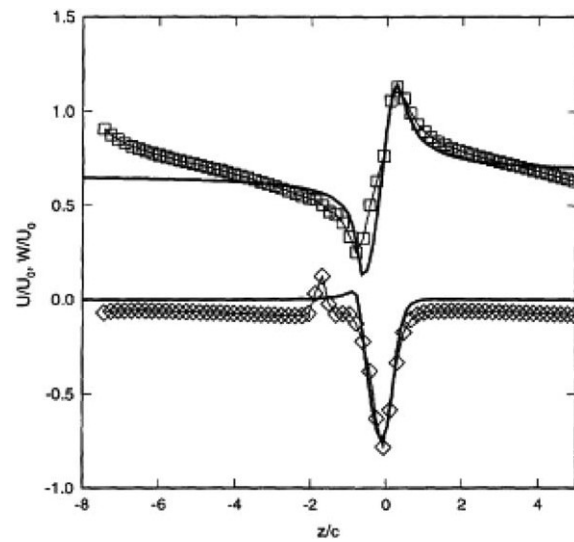


Fig. 18. Comparison of axial (top) and tangential (bottom) velocity patterns occurring at a blade passage (from [48]).

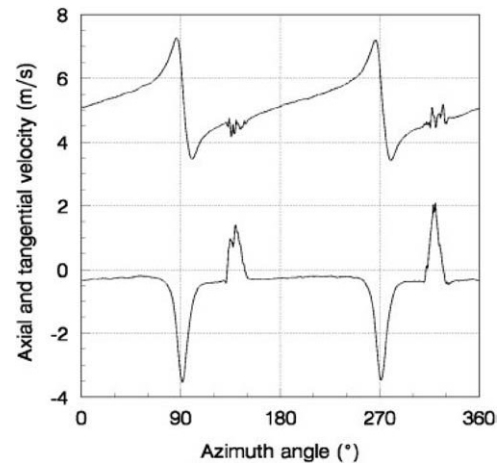


Fig. 19. Measured axial (top) and tangential (bottom) velocity components as a function of rotor azimuth angle (from [24]). The blades pass at 90° and 270° azimuth angle.

rotor blade, also the vorticity distribution over the thickness of the blade has to be accounted for. A simulation was done to compare a single line vortex (as used in the study), with a vortex panel method (XFOIL, see [60]) with a distribution of vortices over the contour of the aerofoil, see Fig. 21. The vorticity distribution results in a different velocity fluctuation and the difference resembles the one from the analysis model, see Figs. 22 and 20.

3.4.2. Tip vortex properties

Besides wake velocities, also the properties of the tip vortices are worthwhile to investigate, because they

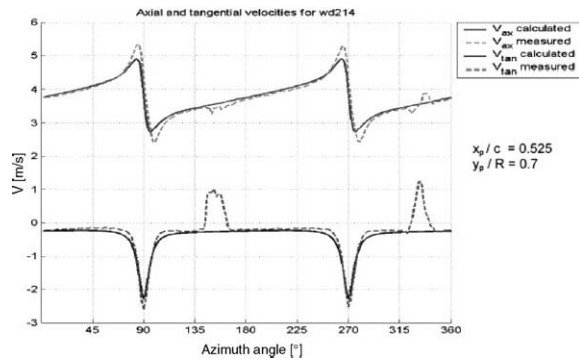


Fig. 20. Measured axial (top) and tangential (bottom) velocities as a function of rotor azimuth angle, compared to calculated velocities (from [59]).

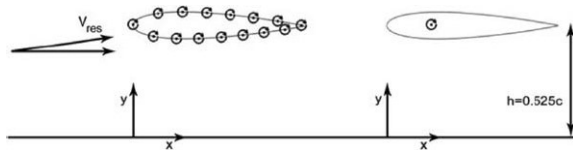


Fig. 21. Modelling of an aerofoil using a vortex distribution over its profile and a single vortex at its quarter chord point (from [59]).

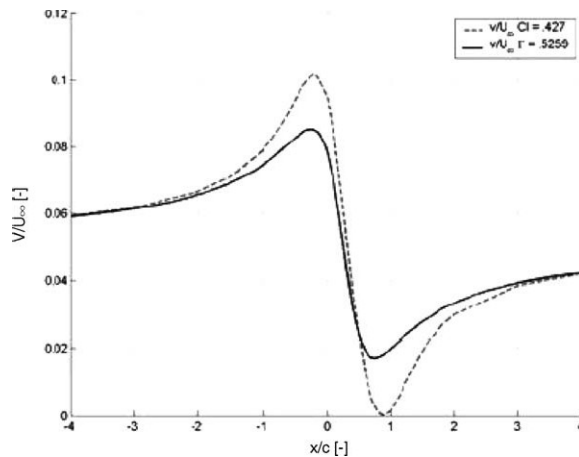


Fig. 22. Induced velocity in the near wake by a model with vortex distribution over its profile, compared to a single vortex model, see Fig. 21 (from [59]).

likewise determine the physical behaviour of the wind turbine rotor as a whole. In this respect, the interesting properties are: wake expansion (as defined by the tip vortex path), vortex spiral twist angle and also the strength of the tip vortex spiral itself. Experiments focussed on this particular area have been carried out by

Vermeer [61–64], Whale et al. [45], Grant [65] and Fisichella [51].

In a series of short experiments, the above mentioned properties have been investigated by Vermeer. At first, the wake expansion was measured by locating the path of the tip vortex. This appeared to be relatively easy, because the passage of the tip vortex core along the hot-wire gives a very distinct signal, see Fig. 23.

Next a similar approach from reducing the bound vorticity has been applied to the free tip vortex in order to determine its strength: when traversing from the passage of the tip vortex further outward in radial direction, the influence of the tip vortex diminishes, see Fig. 24. From this decrease, the strength of the tip vortex can be estimated, see Fig. 25.

Vermeer [63] also did experiments on the transport velocity of the tip vortex. In a very basic way, this transport velocity was measured by taking the time the tip vortex needs to travel a certain distance, by making axial traverses with a hot-wire. Because of the use of these hot-wires, also the local flow velocity was recorded. It appeared that the propagation speed of the tip vortex spiral was lower than the local flow velocity. This can be understood by thinking of the self-induced propagation speed of a vortex ring in still air.

Whale has studied the tip vortex using PIV in a watertank and has made comparison with a vortex lattice method, see Fig. 26. Qualitative agreement is shown for the shape of the wake boundary, including downstream wake contraction, and even at the low Reynolds numbers (6400 to 16,000), quantitative agreement is shown for the tip vortex pitch.

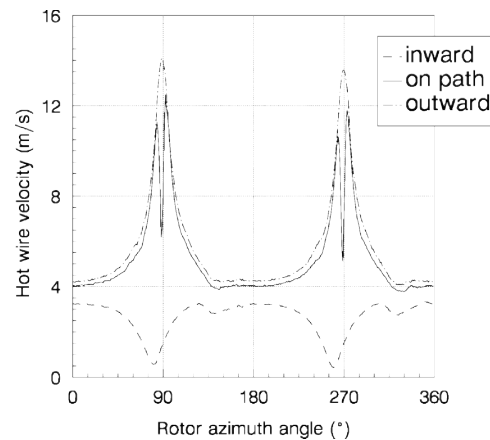


Fig. 23. Typical velocity signal when traversing over the wake boundary to detect vortex path (from [61]). The axial velocity is shown as function of rotor azimuth angle, with the tip vortex occurrences at 90° and 270°. Three radial positions are given: inside and outside of the vortex path and exactly on the vortex path, with the dip in velocity indicating the passage of the vortex core.

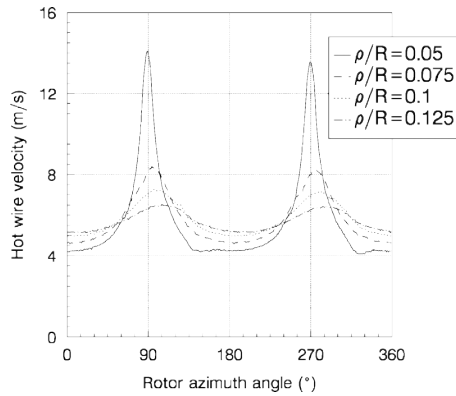


Fig. 24. Azimuthal velocity plot outside the wake boundary, showing the passage of the tip vortices at 90° and 270° azimuth angle (from [62]). The parameter ρ is the radial coordinate measured from the tip radius. The velocity peak associated with the passage of the tip vortex decreases with increasing radial distance.

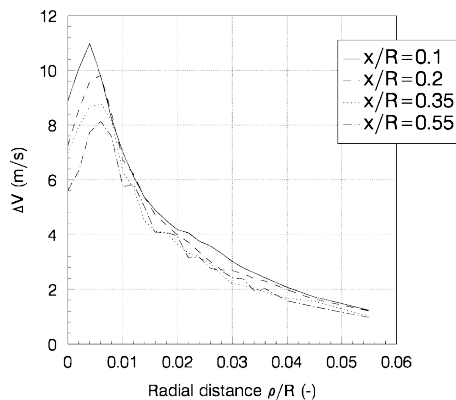


Fig. 25. The value of the peak velocity associated with the passage of the tip vortex (see Fig. 24), as a function of the radial distance from the rotor tip, for several axial distances (from [62]).

Grant [65] has used Laser sheet visualisation to measure the behaviour of the vorticity trailing from the turbine blade tips and the effect of wall interference on wake development, for various conditions of turbine yaw. Results were compared with a prescribed wake model, see Fig. 27.

4. Near wake computations

Although there exists a large variety of methods for predicting performance and loadings of wind turbines, the only approach used today by wind turbine manufacturers is based on the blade element/momentum

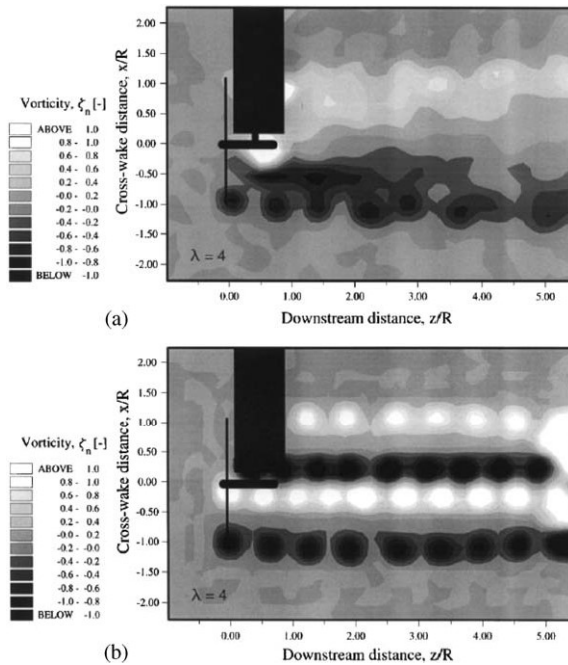


Fig. 26. Comparison of PIV measurements and ROVLM computations of vorticity contour plots of the full wake of a two-bladed flat-plate rotor (from [45]).

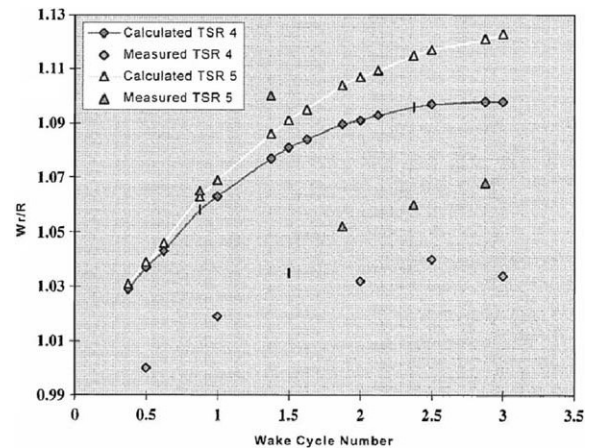


Fig. 27. Predicted and measured wake expansion for tip-speed ratios 4 and 5 in head-on flow (from [65]).

(BEM) theory. A basic assumption in the BEM theory is that the flow takes place in independent stream tubes and that the loading is determined from two-dimensional sectional aerofoil characteristics. The advantage of the model is that it is easy to implement and use on a computer, it contains most of the physics representing rotary aerodynamics, and it has proven to be accurate for the most common flow conditions and rotor

configurations. A drawback of the model is that it, to a large extent, relies on empirical input which is not always available. Even in the simple case of a rotor subject to steady axial inflow, aerofoil characteristics have to be implemented from wind tunnel measurements. The description is further complicated if we look at more realistic operating situations. Wind turbines are subject to atmospheric turbulence, wind shear from the ground effect, wind directions that change both in time and in space, and effects from the wake of neighbouring wind turbines. These effects together form the ordinary operating conditions experienced by the blades. As a consequence, the forces vary in time and space and a dynamical description is an intrinsic part of the aerodynamic analysis.

At high wind velocities, where a large part of the blade operates in deep stall, the power output is extremely difficult to determine within an acceptable accuracy. The most likely explanation for this is that the flow is not adequately modelled by static, two-dimensional aerofoil data. When separation occurs in the boundary layer, outward spanwise flow generated by centrifugal and coriolis pumping tends to decrease the boundary layer thickness, resulting in the lift coefficient being higher than what would be obtained from wind tunnel measurements on a non-rotating blade. Employing a viscous-inviscid interaction technique it has been shown by Sørensen [66] that the maximum lift may increase by more than 30% due to the inclusion of rotational effects. Later experiments of e.g. Butterfield [67], Ronsten [68], and Madsen and Rasmussen [69] have confirmed this result. To take into account the rotational effects, it is common to derive synthesized three-dimensional aerofoil data (see e.g. [70] or Chaviaropoulos and Hansen [71]). If it turns out, however, that stall on a rotating blade inherently is a three-dimensional process, it is doubtful if general values for modifying two-dimensional aerofoil characteristics can be used at high winds. In all cases there is a need to develop three-dimensional models from which parametrical studies can be performed.

When the wind changes direction, misalignment with the rotational axis occurs, resulting in yaw error. This causes periodic variations in the angle of attack and invalidates the assumption of axisymmetric inflow conditions. Furthermore, it gives rise to radial flow components in the boundary layer. Thus, both the aerofoil characteristics and the wake are subject to complicated three-dimensional and unsteady flow behaviour, which only in an approximate way can be implemented in the standard BEM method. To take into account yaw misalignment, modifications to the BEM model have been proposed by e.g. Goankar and Peters [72], Hansen [73], van Bussel [74] and Hasegawa et al. [75]. But, again, a better understanding demands the use of more representative models.

A full description of the global flow field around a wind turbine is in principle possible by solving the Navier–Stokes equations subject to unsteady inflow and rotational effects. In practice, however, the capability of present computer technology limits the number of mesh points to a maximum of about 10 millions, which is not always sufficient for a global description that includes the boundary layer on the rotor as well as and the shed vortices in the wake. As a consequence, various models have been proposed, ranging from models based on potential flow and vortex theory to CFD models based on solving the Reynolds-averaged Navier–Stokes equations.

In the following an overview of computational methods for use in wind turbine aerodynamics will be presented. The intention is not to give here an exhaustive description of numerical techniques. Rather the presentation will concentrate on describing basic features of models pertinent to the aerodynamics of horizontal-axis wind turbines.

4.1. The Navier–Stokes equations

As basic mathematical model we consider the Reynolds-averaged, incompressible Navier–Stokes equations which, with $\vec{V}$ denoting the Reynolds-averaged velocity and P the pressure, in conservative form are written as

$$\frac{\partial \vec{V}}{\partial t} + \nabla \cdot (\vec{V} \otimes \vec{V}) = -\frac{1}{\rho} \nabla P + \nu \nabla \cdot \left[\left(1 + \frac{\nu_t}{\nu} \right) \nabla \vec{V} \right] + \vec{f}, \quad (1)$$

$$\nabla \cdot \vec{V} = 0, \quad (2)$$

where t denotes time, ρ is the density of the fluid and ν is the kinematic viscosity. The Reynolds stresses are modelled by the eddy-viscosity, ν_t , and a body force, $\vec{f}$, is introduced in order to model external force fields, as done in the generalized actuator disc model. These equations constitute three transport equations, which are parabolic in time and elliptic in space, and an equation of continuity stating that the velocity is solenoidal. The main difficulty of this formulation is that the pressure does not appear explicitly in the equation of continuity. The role of the pressure, however, is to ensure the continuity equation be satisfied at every time instant. A way to circumvent this problem is to relate the pressure to the continuity equation by introducing an artificial compressibility term into this (see e.g. [76]). Thus, an artificial transport equation for the pressure is solved along with the three momentum equations, ensuring a solenoidal velocity field when a steady state is achieved. The drawback of this method is that only time-independent problems can be considered. Another approach, the pressure correction method, is to

relate the velocity and pressure fields through the solution of a Poisson equation for the pressure. This is obtained by taking the divergence of the momentum equations, resulting in the following relation:

$$\nabla^2 P = -\rho \nabla \cdot [\nabla \cdot (\vec{V} \otimes \vec{V}) - v_t \nabla \vec{V}], \quad (3)$$

which is solved iteratively along with the momentum equations.

As an alternative to the $\vec{V} - P$ formulation of the Navier–Stokes equations, vorticity based models may be employed, see [77,78]. The vorticity, defined as the curl of the time-averaged velocity

$$\vec{\omega} = \nabla \times \vec{V}, \quad (4)$$

may be introduced as primary variable by taking the curl of Eq. (1). This results in the following set of equations:

$$\begin{aligned} \frac{\partial \vec{\omega}}{\partial t} + \nabla \times (\vec{\omega} \times \vec{V}) \\ = -v \nabla^2 \left[\left(1 + \frac{v_t}{v} \right) \vec{\omega} \right] + \nabla \times \vec{f} + Q_\omega, \end{aligned} \quad (5)$$

$$\nabla \times \vec{V} = \vec{\omega}, \quad \nabla \cdot \vec{V} = 0, \quad (6)$$

where Q_ω contains some additional second order terms from the curl operation. The equations can be formulated in various ways. The Cauchy–Riemann part of the equations, Eq. (6), may e.g. be replaced by a set of Poisson equations

$$\nabla^2 \vec{V} = -\nabla \times \vec{\omega}. \quad (7)$$

If we consider Eq. (5) in an arbitrarily moving frame of reference we get

$$\begin{aligned} \frac{\partial \vec{\omega}^*}{\partial t} + \nabla \times (\vec{\omega}^* \times \vec{V}) \\ = -v \nabla^2 \left[\left(1 + \frac{v_t}{v} \right) \vec{\omega}^* \right] + \nabla \times \vec{f} + Q_\omega, \end{aligned} \quad (8)$$

where the vorticity vector $\vec{\omega}^*$ refers to the inertial system, i.e. $\vec{\omega}^* = \vec{\omega} + 2\vec{\Omega}$, with $\vec{\Omega} = (\Omega_x, \Omega_y, \Omega_z)$ denoting the angular velocity of the coordinate system.

The advantage of the vorticity–velocity formulation over that of the primitive variables were discussed by Speziale [79]. To summarize, these are: (1) Non-inertial effects arising from a rotation or translation of the frame of reference to an inertial frame enter the problem only through the initial and boundary conditions, as demonstrated in Eq. (8); (2) A solenoidal velocity field is automatically ensured when solving Eq. (6), thus no pressure–velocity coupling is needed; (3) The relation between velocity and vorticity is linear. The disadvantages, on the other hand, are that the Cauchy–Riemann part of the equations are overdetermined, i.e. contains more equations than unknowns, and when replacing this by Eq. (7), three Poisson equations have to be solved instead of the one for the pressure in the primitive variables formulation. Another drawback of the model is that the vorticity field must satisfy the solenoidal

constraint, $\nabla \cdot \vec{\omega} = 0$, which follows directly from Eq. (4). Finally, it should be mentioned that when the formulation is employed to solve flow problems in multiple-connected domains, for each hole in the domain, the equations are subject to the following integral constraint (see e.g. [80])

$$\begin{aligned} \frac{1}{\rho} \oint_l \nabla P \, dl = - \oint_l \left[\frac{\partial \vec{V}}{\partial t} + \nabla \cdot (\vec{V} \otimes \vec{V}) \right] dl \\ + v \oint_l \nabla \cdot \left[\left(1 + \frac{v_t}{v} \right) \nabla \vec{V} \right] dl, \end{aligned} \quad (9)$$

where l is an arbitrary circuit looping the inner body.

In a study by Hansen [81] it was concluded that the vorticity–velocity formulation is not well suited to handle high Reynolds number problems in complicated domains, but is a valuable tool for simulations of basic flow problems in Cartesian or cylindrical coordinates.

4.2. Vortex wake modelling

Vortex wake models denote a class of methods in which the rotor blades and the trailing and shed vortices in the wake are represented by lifting lines or surfaces. At the blades the vortex strength is determined from the bound circulation which is related to the local inflow field. The global flow field is determined from the induction law of Biot–Savart, where the vortex filaments in the wake are convected by superposition of the undisturbed flow and the induced velocity field. The trailing wake is generated by spanwise variations of the bound vorticity along the blade. The shed wake is generated by the temporal variations as the blade rotate. Assuming that the flow in the region outside the trailing and shed vortices is curl-free, the overall flow field can be represented by the Biot–Savart law. This is most easily shown by decomposing the velocity in a solenoidal part and a rotational part, using Helmholtz decomposition:

$$\vec{V} = \nabla \times \vec{A} + \nabla \Phi, \quad (10)$$

where $(\vec{A})$ is a vector potential and Φ a scalar potential.

The vector potential automatically satisfies the continuity equation, Eq. (2), and from the definition of vorticity, Eq. (4), we get

$$\nabla^2 \vec{A} = -\vec{\omega}. \quad (11)$$

In the absence of boundaries, this can be expressed as an integral relation,

$$\vec{A}(\vec{X}) = \frac{1}{4\pi} \int \frac{\vec{\omega}'}{|\vec{X} - \vec{X}'|} dV_{ol}, \quad (12)$$

where $\vec{X}$ denotes the point where the potential is computed and the integration is taken over the region where the vorticity is non-zero, designated by V_{ol} . From the definition, Eq. (10), the resulting velocity field is

obtained by

$$\vec{V}(\vec{X}) = -\frac{1}{4\pi} \int \frac{(\vec{X} - \vec{X}') \times \vec{\omega}'}{|\vec{X} - \vec{X}'|^3} dV_{ol}, \quad (13)$$

which is the most usual form of the Biot–Savart law.

In its simplest form the wake is prescribed as a hub vortex plus a spiralling tip vortex or as a series of ring vortices. In this case the vortex system is assumed to consist of a number of line vortices with vorticity distribution

$$\omega(\vec{X}) = \Gamma \delta(\vec{X} - \vec{X}'), \quad (14)$$

where Γ is the circulation, δ is the Dirac delta function and $\vec{X}'$ is the curve defining the location of the vortex lines. Combining this with Eq. (13) results in

$$\vec{V}(\vec{X}) = -\frac{1}{4\pi} \int_S \Gamma \frac{(\vec{X} - \vec{X}')}{|\vec{X} - \vec{X}'|^3} \times \frac{\partial \vec{X}'}{\partial s'} ds', \quad (15)$$

where S is the curve defining the vortex line and s' is the parametric variable along the curve. Utilizing Eq. (15), simple vortex models can be derived to compute quite general flow fields about wind turbine rotors. In a study of Miller [82], a system of vortex rings was used to compute the flow past a heavily loaded wind turbine. It is remarkable that in spite of the simplicity of the model, it was possible to simulate the vortex ring/turbulent wake state with good accuracy, as compared to the empirical correction suggested by Glauert [2]. As a further example, a similar simple vortex model developed by Øye [83] was used to calculate the relation between thrust and induced velocity at the rotor disc of a wind turbine, in order to validate basic features of the streamtube-momentum theory. The model includes effects of wake expansion, and, as in the model of Miller, it simulates a rotor with an infinite number of blades, with the wake being described by vortex rings. From the model it was found that the axial induced velocities at the rotor disc are smaller than those determined from the ordinary streamtube-momentum theory. Based on the results a correction to the momentum method was suggested. Although the correction is small, an important conclusion was that the apparent underestimation of the power coefficient by the momentum method is not primarily caused by its lack of detail regarding the near wake, but is more likely caused by the decay of the far wake. A similar approach has been utilised by Wood and co-workers [84,85].

To compute flows about actual wind turbines it becomes necessary to combine the vortex line model with tabulated two-dimensional aerofoil data. This can be accomplished by representing the spanwise loading on each blade by a series of straight vortex elements located along the quarter chord line. The strength of the vortex elements are determined by employing the Kutta–Joukowski theorem on the basis of the local aerofoil characteristics. As the loading varies along the span of

each blade the value of the bound circulation changes from one filament to next. This is compensated for by introducing trailing vortex filaments whose strengths correspond to the differences in bound circulation between adjacent blade elements. Likewise, shed vortex filaments are generated and convected into the wake whenever the loading undergoes a temporal variation. While vortex models generally provide physically realistic simulations of the wake structure, the quality of the obtained results depends crucially on the input aerofoil data. Indeed, in order to be of practical use, aerofoil data has to be modified with respect to three-dimensional effects and dynamic stall. In particular the American NREL experiment in the wind tunnel at NASA-Ames has demonstrated that, even though two-dimensional aerofoil data exist, input aerofoil data are the main source of uncertainty and errors in load predictions, see [14].

In vortex models, the wake structure can either be prescribed or computed as a part of the overall solution procedure. In a prescribed vortex technique, the position of the vortical elements is specified from measurements or semi-empirical rules. This makes the technique fast to use on a computer, but limits its range of application to more or less well-known steady flow situations. For unsteady flow situations and complicated wake structures free wake analysis becomes necessary. A free wake method is more straightforward to understand and use, as the vortex elements are allowed to convect and deform freely under the action of the velocity field. The advantage of the method lies in its ability to calculate general flow cases, such as yawed wake structures and dynamic inflow. The disadvantage, on the other hand, is that the method is far more computing expensive than the prescribed wake method, since the Biot–Savart law has to be evaluated for each time step taken. Furthermore, free wake vortex methods tend to suffer from stability problems owing to the intrinsic singularity in induced velocities that appears when vortex elements are approaching each other. This can to a certain extent be remedied by introducing a vortex core model in which a cut-off parameter models the inner viscous part of the vortex filament. In recent years much effort in the development of models for helicopter rotor flowfields have been directed towards free-wake modelling using advanced pseudo-implicit relaxation schemes, in order to improve numerical efficiency and accuracy (e.g. [86,87]).

To analyse wakes of horizontal axis wind turbines, prescribed wake models have been employed by e.g. Gould and Fiddes [88], Robison et al. [89], and Coton and Wang [90], and free vortex modelling techniques have been utilised by e.g. Afjeh and Keith [91] and Simoes and Graham [92]. A special version of the free vortex wake methods is the method by Voutsinas [93] in which the wake modelling is taken care of by vortex

particles or vortex blobs. Recently, the model of Coton and co-workers [94] was employed in the NREL blind comparison exercise [14], and the main conclusion from this was that the quality of the input blade sectional aerodynamic data still represent the most central issue to obtaining high-quality predictions.

A generalisation of the vortex method is the so-called *boundary integral equation method* (BIEM), where the rotor blade in a simple vortex method is represented by straight vortex filaments, the BIEM takes into account the actual finite-thickness geometry of the blade. The theoretical background for BIEMs is potential theory where the flow, except at solid surfaces and wakes, is assumed to be irrotational. In such a case the velocity field can be represented by a scalar potential,

$$\vec{V} = \nabla \Phi, \quad (16)$$

where the velocity potential

$$\Phi = \phi_\infty + \phi, \quad (17)$$

is decomposed into a potential ϕ_∞ representing the free stream velocity, and a perturbation potential ϕ that through the continuity equation, Eq. (2), can be expressed as

$$\nabla^2 \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0. \quad (18)$$

Integrating this equation over discontinuity surfaces, here denoted S , Green's theorem yields

$$\phi = -\frac{1}{4\pi} \int_S \sigma \frac{1}{|\vec{X} - \vec{X}'|} dS - \frac{1}{4\pi} \int_S \mu \frac{\partial}{\partial n} \frac{1}{|\vec{X} - \vec{X}'|} dS, \quad (19)$$

where n is the coordinate normal to the wall, σ is the source distribution and μ is the doublet distribution. These represent the singularities at the border of the flow domain, i.e. at solid surfaces and wakes. In a rotor computation the blade surface is covered with both sources and doublets while the wake only is represented by doublets (see e.g. [95] or [96]). The circulation of the rotor is obtained as an intrinsic part of the solution by applying the Kutta condition on the trailing edge of the blade. The main advantage of the BIEM is that complex geometries can be treated without any modification of the model. Thus, both the hub and the tower can be modelled as a part of the solution. Furthermore, the method does not depend on aerofoil data and viscous effects can, at least in principle, be included by coupling the method to a viscous solver. Within the field of wind turbine aerodynamics, BIEMs has been applied by e.g. Preuss et al. [97], Arsuffi [98] and Bareiss and Wagner [99]. Up to now, however, only simple flow cases have been considered.

A method in line with the BIEM is the asymptotic acceleration potential method, developed originally for helicopter aerodynamics by van Holten [100] and

later developed further to cope with wind turbines by van Bussel [101]. The method is based on solving a Poisson equation for the pressure, assuming small perturbations of the mean flow. The model has been largely used by van Bussel [101] to analyse various phenomena within wind turbine aerodynamics. Computational efficiency and range of application of the method corresponds to what is obtained by prescribed vortex wake models.

4.3. Generalized actuator disc models

In fluid mechanics the actuator disc is defined as a discontinuous surface or line on which surface forces act upon the surrounding flow. In rotary aerodynamics the concept of the actuator disc is not new. Indeed, the actuator disc constitutes the main ingredient in the one-dimensional momentum theory, as formulated by Froude [102], and in the 'classical' BEM method by Glauert [2]. Usually, the actuator disc is employed in combination with a simplified set of equations and its range of applicability is often confused with the particular set of equations considered. In the case of a horizontal axis wind turbine the actuator disc is given as a permeable surface normal to the freestream direction on which an evenly distribution of blade forces acts upon the flow. In its general form the flow field is governed by the unsteady, axisymmetric Euler or Navier–Stokes equations, which means that no physical restrictions need to be imposed on the kinematics of the flow.

The first non-linear actuator disc model for heavily loaded propellers was formulated by Wu [103]. Although no actual calculations were carried out, this work demonstrated the opportunities for employing the actuator disc on complicated configurations as e.g. ducted propellers and propellers with finite hubs. Later improvements, especially on the numerical treatment of the equations, are due to e.g. [104,105], and recently Conway [106,107] has developed further the analytical treatment of the method. In the application of the actuator disc concept for wind turbine aerodynamics, the first non-linear model was suggested by Madsen [108], who developed an actuator cylinder model to describe the flow field about a vertical-axis wind turbine, the Voight–Schneider or Gyro mill. This model has later been adapted to treat horizontal axis wind turbines. A thorough review of 'classical' actuator disc models for rotors in general and wind turbines in particular can be found in the dissertation by van Kuik [109]. Recent developments of the method has mainly been directed towards the use of Navier–Stokes equations.

In helicopter aerodynamics combined Navier–Stokes/actuator disc models have been applied by e.g. Fejtek and Roberts [110] who solved the flow about a helicopter employing a chimera grid technique in

which the rotor was modelled as an actuator disk, and Rajagopalan and Mathur [111] who modelled a helicopter rotor using time-averaged momentum source terms in the momentum equations.

In a numerical actuator disc model, the Navier–Stokes (or Euler) equations, Eqs. (1)–(3) or Eqs. (5)–(7), are typically solved by a second order accurate finite difference/volume scheme, as in a usual CFD computation. However, the geometry of the blades and the viscous flow around the blades are not resolved. Instead the swept surface of the blades is replaced by surface forces that act upon the incoming flow at a rate corresponding to the period-averaged mechanical work that the rotor extracts from the flow.

In the simple case of an actuator disc with constant prescribed loading, various fundamental studies can easily be carried out. Comparisons with experiments have demonstrated that the method works well for axisymmetric flow conditions and can provide useful information regarding basic assumptions underlying the momentum approach [112–115], turbulent wake states occurring for heavily loaded rotors [115,116], and rotors subject to coning [117,118].

When computing the flow past an actual wind turbine, the aerodynamic forces acting on the rotor are determined from two-dimensional aerofoil characteristics, corrected for three-dimensional effects, using a blade-element approach.

In Fig. 28, a cross-sectional element at radius r defines the aerofoil in the (θ, z) plane. Denoting the tangential and axial velocity in the inertial frame of reference as V_θ and V_z , respectively, the local velocity relative to the rotating blade is given as

$$V_{\text{rel}} = (V_\theta - \Omega r, V_z). \quad (20)$$

The angle of attack is defined as

$$\alpha = \phi - \gamma, \quad (21)$$

where $\phi = \tan^{-1}(V_z/(\Omega r - V_\theta))$ is the angle between V_{rel} and the rotor plane and γ is the local pitch angle. The

distribution of surface forces, i.e. forces per unit rotor area, is given by the following expression:

$$f_{2D} = \frac{dF}{dA} = \frac{1}{2} \rho V_{\text{rel}}^2 c B (C_L e_L + C_D e_D) / (2\pi r), \quad (22)$$

where $C_L = C_L(\alpha, Re)$ and $C_D = C_D(\alpha, Re)$ are the lift and drag coefficients, respectively, c is the chord length, B denotes the number of blades, and e_L and e_D denote the unit vectors in the directions of the lift and the drag, respectively. The lift and drag coefficients are determined from measured or computed two-dimensional aerofoil data that are corrected for three-dimensional effects. There are several reasons why it is necessary to correct the aerofoil data. First, at separation rotational effects limit the growth of the boundary layer, resulting in an increased lift as compared to two-dimensional characteristics. Various correction formulas for rotational effects have been derived using quasi three-dimensional approaches (see e.g. [120,71]). Next, the aerofoil characteristics depend on the aspect ratio of the blade. This is in particular pronounced at high incidences where the finite aspect ratio drag coefficient, C_D , is much smaller than the corresponding one for an infinite blade. As an example, for a flat plate at an incidence $\alpha = 90^\circ$ the drag coefficient $C_D = 2$ for an infinitely long plate, whereas for aspect ratios corresponding to the geometry of a wind turbine blade C_D takes values in the range 1.2–1.3. In [121] it is stated that the normal force from a flat plate is approximately constant for $45^\circ < \alpha < 135^\circ$, indicating that in this range both C_L and C_D have to be reduced equally. Hansen [122] proposes to reduce C_L and C_D by an expression that takes values in range from 0.6 to 1.0, depending on the ratio between the distance to the tip and the local chord length. It should be noticed, however, that this is only a crude guideline and that most aerofoil data for wind turbine use is calibrated against actual performance and load measurements. This also explains why most manufacturers of wind turbine blades are reluctant to change well-tested aerofoil families. Yet a correction concerns unsteady phenomena related to boundary layer separation, referred to as dynamic stall. For aerofoils undergoing large temporal variations of the angle of attack, the dynamic response of the aerodynamic forces exhibits hysteresis that changes the static aerofoil data. Dynamic stall models have been developed and applied on wind turbines by e.g. Øye [123] or Leishman and Beddoes [124].

Computations of actual wind turbines employing numerical actuator disc models in combination with a blade-element approach have been carried out by e.g. Sørensen et al. [112,113] and Masson et al. [125,126] in order to study unsteady phenomena. Wakes from coned rotors have been studied by Madsen and Rasmussen [117], Masson [126], and Mikkelsen et al. [118], rotors operating in enclosures such as wind tunnels or solar

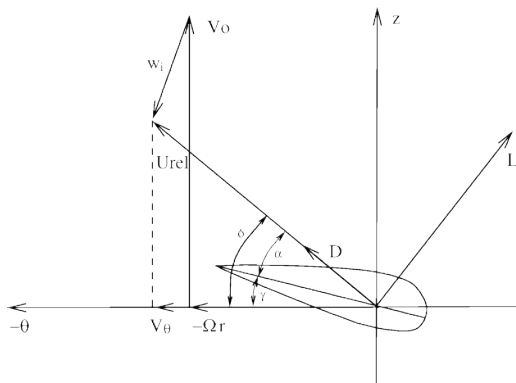


Fig. 28. Cross-sectional aerofoil element (from [119]).

chimneys were computed by Phillips and Schaffarczyk [127], and Mikkelsen and Sørensen [128], and approximate models for yaw have been implemented by Mikkelsen and Sørensen [129] and Masson [126]. Finally, Masson and colleagues have devised techniques for employing their actuator disc model to study the wake interaction in wind farms and the influence of thermal stratification in the atmospheric boundary layer [126,130].

To demonstrate which kind of results can be achieved using an numerical axisymmetric actuator disc model, in Figs. 29 and 30 we show computed stream lines for the flow field about the Tjæreborg wind turbine at two different wind speeds. Noteworthy is the details of unsteady flow behaviour that can be obtained at small wind velocities. In fact, the streamline shown in Fig. 29 corresponds to the turbulent wake state. A main feature of the numerical actuator disc technique is the possibility of predicting transient and unsteady flow behaviour. For wind turbines unsteady effects occurs when the wind changes speed or direction, or when the rotor is subject to blade pitching actions.

This is shown in Fig. 31 where measured and computed time histories of the flapping moment of the Tjæreborg machine are compared for a case in which the pitch angle was changed in a sequence going from 0° to 2° and then back to 0° , with the value of 2° fixed in 30 s. In the calculations the pitch angle was changed instantaneously, therefore a slight difference between the two curves occurs in the initial and the final stage of the sequence. The overall behaviour of the calculations,

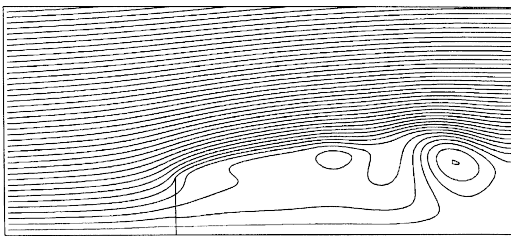


Fig. 29. Flow field about the Tjæreborg wind turbine at a wind speed of 6.5 m/s (from [113]).

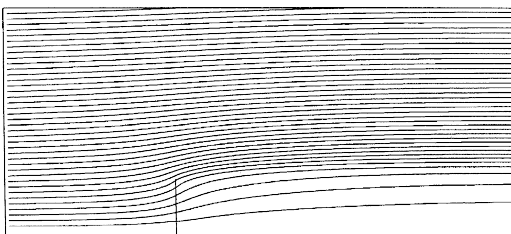


Fig. 30. Flow field about the Tjæreborg wind turbine at a wind speed of 10 m/s (from [113]).

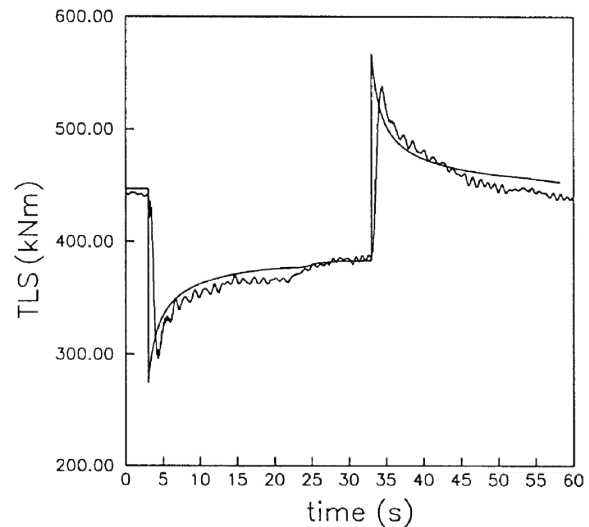


Fig. 31. Transient behaviour of the flapping moment for the Tjæreborg wind turbine subjected to instantaneous blade pitch changes (from [113]).

however, is seen to be in excellent agreement with measured data.

The main limitation of the axisymmetric assumption is that the forces are distributed evenly along the actuator disk, hence the influence of the blades is taken as an integrated quantity in the azimuthal direction. To overcome this limitation, an extended three-dimensional actuator disc model has recently been developed by Sørensen and Shen [119]. The model combines a three-dimensional Navier–Stokes solver with a technique in which body forces are distributed radially along each of the rotor blades. Thus, the kinematics of the wake is determined by a full three-dimensional Navier–Stokes simulation whereas the influence of the rotating blades on the flow field is included using tabulated aerofoil data to represent the loading on each blade. As in the axisymmetric model, aerofoil data and subsequent loading are determined iteratively by computing local angles of attack from the movement of the blades and the local flow field. The concept enables one to study in detail the dynamics of the wake and the tip vortices and their influence on the induced velocities in the rotor plane. The main motivation for developing the model is to analyse and verify the validity of the basic assumptions that are employed in the simpler more practical engineering models. In the following, we show some numerical results from computations of a 500 kW Nordtank wind turbine at a wind speed $V_0 = 10$ m/s, corresponding to a tip speed ratio of 5.8.

Fig. 32 depicts iso-vorticity contours illustrating the downstream development of the wake vortices. The bound vorticity of the blades is seen to be shed

downstream from the rotor in individual vortex tubes. These vortices persist about 2 turns after which they diffuse into a continuous vortex sheet.

Fig. 33 shows the distribution of the axial interference factor, in the rotor plane. The three blades are seen as lines with a high density of iso-lines, owing to the large changes in induced velocity that takes place across the blades. The number of iso-lines is 30 and the value between two successive lines is equidistant. The values range from -0.15 to 0.55 , with peak values appearing near the mid-section of the blades (with a positive value on one side of the blade and a negative value on the other).

The development of the axial velocity distribution in the wake is depicted in Fig. 34. The velocity distributions are averaged in the azimuthal direction and plotted at axial positions $z/R = 0, 1, 2$ and 3 . Outside the wake the value of the axial velocity attains the one of the undisturbed wind. A small overshoot is observed at

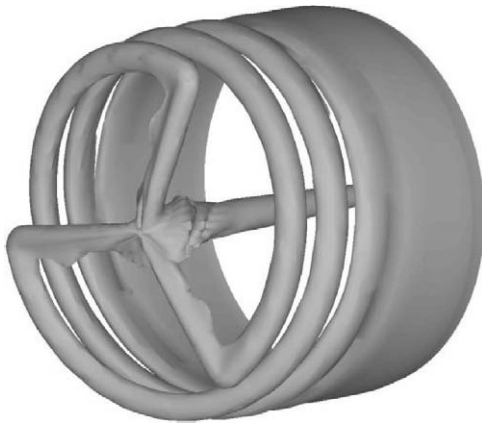


Fig. 32. Computed vorticity field showing the formation of the wake structure about the Tjæreborg wind turbine at a wind speed of 10 m/s (from [119]).

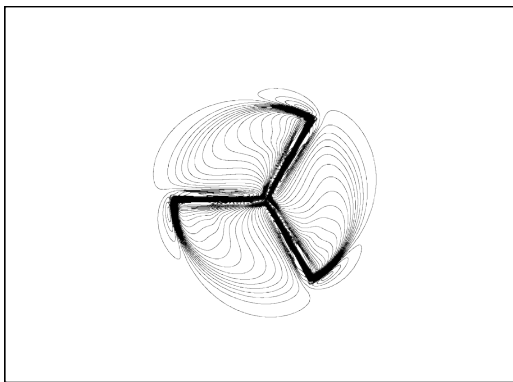


Fig. 33. Distribution of axial interference factor, $a = 1 - V_z/V_0$, in the rotor plane at a wind speed of 10 m/s (from [119]).

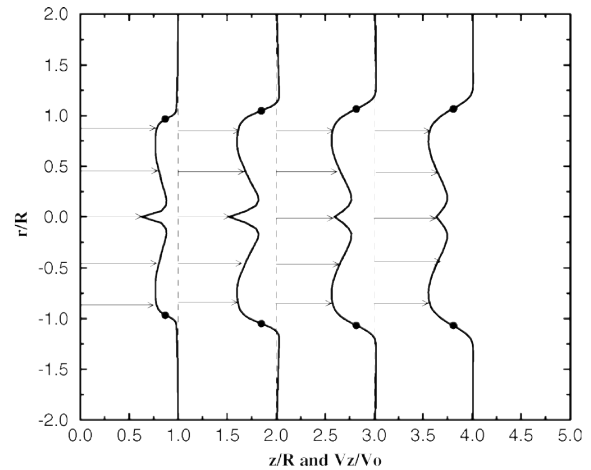


Fig. 34. Distribution of axial velocity at a wind speed of 10 m/s. The core of the tip vortices are marked by • (from [119]).

$z/R = 2$. For all velocity profiles a distinct minimum occurs at $r = 0$. This is caused by the loading on the inner part of the blade that is dominated by large drag forces. The position of the tip vortices is inferred as dots on the velocity profiles. As can be seen they are generally located midway between the wake and the external flow at the position where the gradient of the axial velocity attains its maximum value.

4.4. Navier–Stokes methods

During the past two decades a strong research activity within the aeronautical field has resulted in the development of a series of Computational Fluid Dynamics (CFD) tools based on the solution of the Reynolds-averaged Navier–Stokes (RANS) equations. This research has mostly been related to the aerodynamics of fixed-wing aircraft and helicopters. Some of the experience gained from the aeronautical research institutions has been exploited directly in the development of CFD algorithms for wind turbines. Notably is the development of basic solution algorithms and numerical schemes for solution of the flow equations, grid generation techniques and the modelling of boundary layer turbulence. These elements together form the basis of all CFD codes, of which some already exist as standard commercial software. Looking specifically on the aerodynamics of horizontal axis wind turbines, we find some striking differences as compared to usual aeronautical applications. First, as tip speeds generally never exceeds 100 m/s, the flow around wind turbines is incompressible. Next, the optimal operating condition for a wind turbine always includes stall, with the upper side of the rotor blades being dominated by large areas of flow separation. This is in contrast to the cruise

condition of an aircraft where the flow is largely attached.

The research on CFD in wind turbine aerodynamics has in Europe taken place mostly through the EU-funded collaborate projects VISCWIND [131], VISCEL [132] and the on-going project KNOW-BLADE. The participants in these projects are Risø, DTU, CRES, NTUA, VUB, FFA and DLR, who all have vast experience in developing Navier–Stokes codes. Results from the projects have been reported in e.g. [132–137]. In the US, three-dimensional computations of wind turbine rotors employing Reynolds-averaged Navier–Stokes equations have been carried out by Duque et al. [138,139] and by Xu and Sankar [140,141], who utilised a hybrid Navier–Stokes/full-potential/free wake method in order to reduce computing time.

Recently, the American NREL experiment at NASA-Ames [142] and the accompanying NREL/NWTC Aerodynamics Blind Comparison test [14] have given a lot of new insight into wind turbine aerodynamics and revealed serious shortcomings in present day wind turbine aerodynamics prediction tools. First, computations of the performance characteristics of the rotor by methods based on blade element techniques were found to be extremely sensitive to the input blade section aerodynamic data [94,143]. Indeed, predicted values of the distribution of the normal force coefficient deviated from measurements by as much as 50%. Even at low angles of attack, model predictions differed from measured data by 15–20% [14]. Next, the computations based on Navier–Stokes equations convincingly showed that CFD has matured to become a tool for predicting and understanding the flow physics of modern wind turbine rotors. The Navier–Stokes computations by Sørensen et al. [144] generally exhibited very good agreement with the measurements, except at a wind speed of 10 m/s. At this particular wind speed, onset of flow separation is taking place. Hence, it is likely that the introduction of a more physically consistent turbulence modelling and the inclusion of a laminar/turbulent transition model will improve the quality of the results. In the following we give a short description of basic elements and research areas that generally are acknowledged to be of importance for CFD solutions of wind turbine rotors.

4.4.1. Turbulence modelling

To model the Reynolds stresses various turbulence models are available, ranging from simple algebraic zero-equation models to two-equation transport models and system of transport equations for the Reynolds stresses. The turbulence modelling in itself has been an important subject for many years and the research activities within the field will probably continue for the next many years to come. Along with laminar–turbulent transition, turbulence modelling constitutes the most

critical part of the flow modelling, as they do not have a universal validity, and for most practical applications, various parameters have to be calibrated to empirical data. Some of the most popular models are still the Baldwin–Lomax zero-equation model [145] and the two-equation k – ε model [146], although they exhibit problems in reproducing correctly stall characteristics of aerofoils and rotor blades (see e.g. [147,148]). In the past years refined one- and two-equation turbulence models have been developed to cope with specific flow features. In particular the k – ω SST model developed by Menter [149] has shown its capability to cope with attached and lightly separated aerofoil flows, and today this model is widely used for wind turbine computations [144]. As an alternative to the Reynolds-averaged methodology large eddy simulation (LES) techniques have been widely explored in the past years. Although LES gives a better physical representation of the eddy dynamics in separated flows, it is still limited to flow problems at moderate Reynolds numbers. As the RANS equations fail to simulate massive separation, even when simulations are performed in a time-true sense, and large eddy simulations (LES) are unaffordable, hybrid LES/RANS approaches, such as detached eddy simulation (DES), represent an attractive compromise between computing costs and accuracy. The idea behind hybrid approaches is to combine fine-tuned RANS technology in the boundary layers, and the simple power of LES in the separated regions, see [150]. In the RANS regions, the turbulence model has full control over the solution through the eddy-viscosity based closure. In the LES region, little control is left to the model, the larger eddies are resolved both in space and time, and grid refinement directly expands the range of scales in the solution. This reduces considerably the computing costs as compared to a full blown LES. The DES technique has recently been applied on the NREL Phase VI wind turbine blade under parked conditions by Johansen et al. [151].

4.4.2. Laminar–turbulent transition

Most computations of flows around rotor blades are carried out assuming that the boundary layer is fully turbulent everywhere. However, recent computational results indicate that correct treatment of flow transition is important for capturing the flow physics of aerofoils and rotor blades during stall and post-stall. There are at least two different forms of transition. If the incoming flow is largely laminar, natural transition is encountered, whereas for highly turbulent incoming flow or flow over rough surfaces, such as often found in wind engineering, the so-called *bypass* transition occurs. To predict free transition, several engineering methods based on linear stability analysis may be utilised. These range from empirical one-step methods, such as the Michel criterion [152], to methods based on solution to the Orr–Sommerfeldt equations, such as the e^n database method

of Stock and Degenhart [153]. In principle a transition prediction can take place by solving the RANS along with the Orr–Sommerfeldt equations. However, this has shown to be difficult and not very robust. Hence, most efforts have been directed towards the use of integral boundary layer methods to obtain integral boundary layer parameters, such as momentum thickness and shape parameter [137]. These are subsequently used as input to the transition model. For bypass transition, only empirical methods are presently available. Such methods rely entirely on experimental data and for bypass transition on aerodynamic configurations the body of experimental knowledge is very limited.

Within the field of wind turbine aerodynamics, transition models have for two-dimensional aerofoils been examined by Johansen and Sørensen [154], Brodeur and van Dam [155], Xu and Sankar [141], and Michelsen and Sørensen [137]. By Johansen and Sørensen [154], it was clearly demonstrated that transition prediction can be of utmost importance. For the flow past a FX 66-196 VI aerofoil, an underprediction of the lift coefficient of about 20% was obtained when assuming fully turbulent flow, whereas the use of a database method for transition prediction resulted in predictions within 1% up to stall and a small overprediction of maximum lift of about 4%.

In three dimensions transition predictions involve a number of additional complications that still remains unsolved. The determination of the stagnation point is not obvious, since it forms a line with an a priori unknown position. The boundary layer equations are more complex and involves cross-flow effects. Further, they need to be integrated along the flow on the edge of the boundary layer.

5. Far wake experiments

The far wake is the region located downstream of the near wake previously studied. As explained before, in the near wake region, immediately downstream of the rotor, vortex sheets, associated with the radial variation in circulation along the blades, are shed from their trailing edge, and roll up in a short downstream distance forming tip vortices that describe helical trajectories, as can be seen in Figs. 4–8 and 32. When the inclination angle of the helix is small enough, the layer, in which the tip vortices are located, can be interpreted as a cylindrical shear layer which separates the slow moving fluid in the wake from that on the outside. Because of turbulent diffusion, the thickness of the shear layer increases with downstream distance. Most of the turbulence that makes the wake diffuse is, at this stage, created by the shear in the wake, mainly in the shear layer. However, the shear in the external atmospheric flow also plays an important role, at least in the

redistribution of the generated turbulence. At a certain distance downstream (about two to five diameters), the shear layer reaches the wake axis. This marks the end of the near wake region. After the near wake region, there is a transition region leading to the far wake region, where the wake is completely developed and, in the hypothetical absence of ambient shear flow, it may be assumed that the perturbation profiles of both velocity deficit and turbulence intensity are axisymmetric, and have self-similar distributions in the cross-sections of the wake. This property of self-similarity is the basis of the kinematic models describing wind turbine wakes. However, the presence of the ground and the shear of the ambient flow invalidate the assumption of axial symmetry and, to some extent, the hypothesis of self-similarity.

As already indicated, it is difficult to separate the research work on the near and far wakes. A typical example is shown in Fig. 35 from [156].

This figure represents the turbulent velocity profile in vertical planes at different downstream stages. It can be seen that in the annular shear layer of the near wake there is a peak in turbulence, that is largest in the upper part. Further downstream, the shear layer has diffused, and the ring-like maxima shrinks to a single maximum, that is located above the turbine axis; this upward location is clearly a reminiscent phenomenon of the near wake. The non-symmetric character of the turbulence distribution in the shear layer, is clearly associated to the non-symmetric character of the incident flow, and the maximum of turbulence in the upper part, could no be predicted with an analysis based on axial symmetry. Other aspect to be considered, when relating the far and near wakes, is that what is interpreted as turbulence in Fig. 35, is, at least partially, ordered motion associated to mean vorticity, in the previous analysis. It could be of

COMPARISON BETWEEN THE MEASURED AND PREDICTED TURBULENT VELOCITY PROFILES IN THE WAKE OF A SINGLE MACHINE OPERATING AT TSR= 4.0.

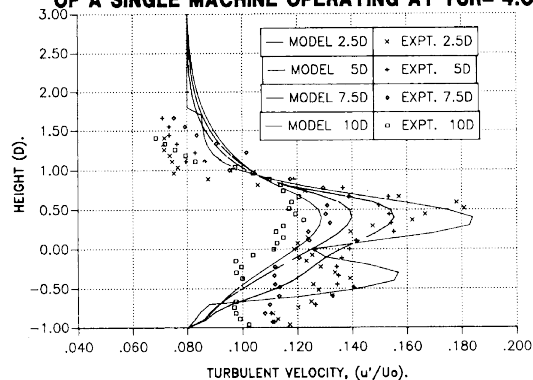


Fig. 35. Vertical turbulent velocity profile at different downstream distances. Comparison of experimental measurements in wind tunnel and model calculations (from [156]).

interest to see how the previous analysis should be modified to take into account the non-symmetric effects, and check, at least qualitatively, if this will result in larger turbulence plus vorticity production in the upper part of the shear layer. As it will be seen in the section on far wake numerics, the analysis made by Smith and Taylor [156], Fig. 35, and those of other authors [157], based on eddy-diffusivity models, and parabolic approximations, are comparatively easy, and even Crespo and Hernández [157] were able to give a theoretical estimation of the near wake peak; however, an analysis based on solving the fully elliptic equations, with complicated non-symmetric boundary conditions could be a formidable problem.

In this section, far wake measurements of both wind tunnel and field experiments will be discussed. A comparison of experimental and numerical results will be made in the following sections. In general, the conditions are better controlled in the wind tunnel experiments and consequently a better agreement with numerical results can be obtained. On the other hand, the reproduction of many aspects of the real situation of the atmospheric and environmental conditions is not easy in wind tunnel experiments, and the size of the models should be small enough to avoid blocking effects. Helmis et al. [158] argue that the length of the near wake region is overestimated in wind tunnel experiments. Högström et al. [159] indicate that wake turbulence intensity may be higher than the corresponding wind tunnel data by a factor of two, whereas velocity deficit is higher in wind tunnel data. A general review of the earlier experimental work on wind wakes prior to 1989 can be found, in [160], and regarding turbulence characteristics in [161].

5.1. Wind tunnel experiments

Most of the wind tunnel experiments were carried out before 1995. They were both for single wakes and for clusters, and were based on model rotors and static simulators. These measurements were on velocity deficits (see Figs. 36 and 37) and on turbulence characteristics (see Fig. 35 from [156]). Vermeulen and Bultjes [162] and Bultjes [163] carried out wind tunnel experiments on static simulators and investigated both velocities and turbulence structure. They found interesting results, confirmed by later research work, such as the saturation of the turbulence, that reaches an equilibrium value within the cluster, after several rows of turbines. They also found that in the wakes there is a shift in the turbulence energy spectrum towards higher frequencies; this effect is confirmed by field experiments. Similar experiments were made by Green [164]. Ross and Ainslie [39] and Ross [165] carried out experiments with rotating models in clusters, that were incorporated to the analysis of Vermeulen and Bultjes [162]; they

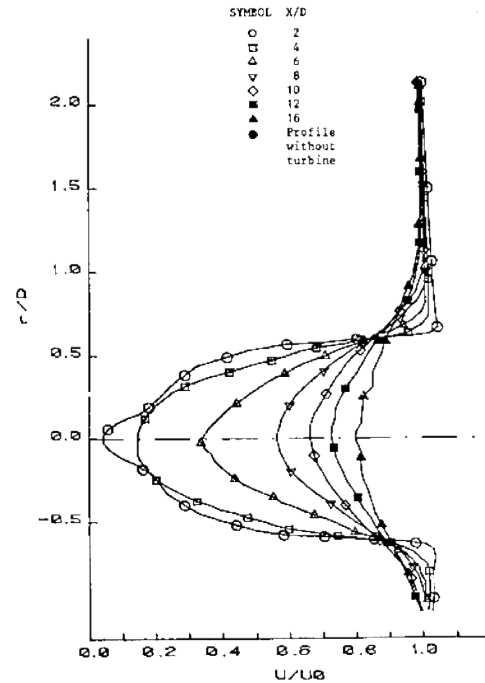


Fig. 36. Mean velocity behind turbine in freestream (from [16]).

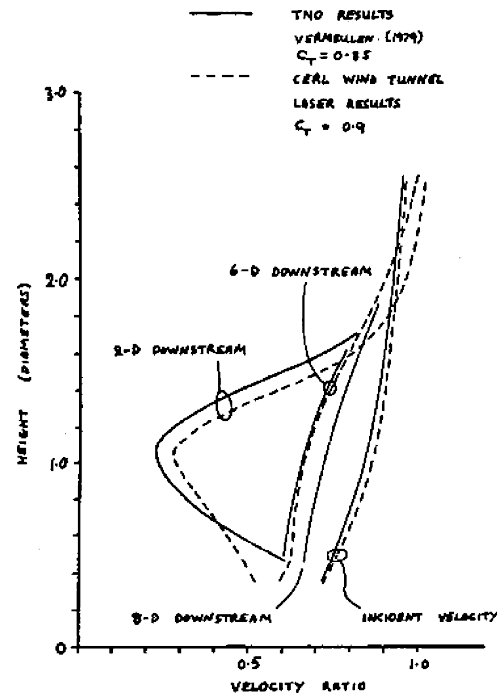


Fig. 37. Velocity deficit in boundary layer (from [39]).

were able to study the influence of the thrust coefficient of the turbine on the equilibrium value of the added turbulence.

Vermeulen and Bultjes [162] also measured the auto-correlation function, for several locations in the cluster, and compared it to the unperturbed upstream value. They found very similar auto-correlation functions for the perturbed flow, so that there is no difference between the turbulence structure after the first row and after multiple rows. This is probably because the typical size of the auto-correlation for all the perturbed flows is always the rotor diameter.

Several authors studied experimentally the influence of different parameters, such as downstream distance: [166,164,167,39], thrust coefficient of the wind turbine: [168,164,167], ambient turbulence: [168–170] on the added turbulence intensity. Some of these measurements have been gathered by Quarton [161] and Crespo and Hernández [157,171], that have developed analytical correlations to estimate the added turbulence intensity in the far wake, that will be presented later (Eqs. (26) and (28)). The turbulence intensity decreases with downstream distance, and increases with the thrust coefficient, but regarding the dependence with ambient turbulence, the results are not consistent, even qualitatively. In general, it is found that turbulence effects are more persistent, and that the decay of the velocity deficit is more rapid than the decay of turbulence intensity; this is also observed in large field experiments. This result is confirmed by field experiments: Højstrup [172] and Högström et al. [159] found that turbulence effects are noticeable even at 12D (diameters) and 10D downstream, respectively, whereas velocity defects are almost negligible at those distances. The correlations given later will also confirm these tendencies.

Smith [173] and Smith and Taylor [156] performed wind tunnel experiments on two rotating models of 0.27 m diameter, one located directly downstream from the other. The scale was 1/300, and they reproduced the atmospheric surface layer with an equivalent full scale roughness of 0.07 m, and a turbulence intensity of 9%. Mean and turbulent velocity and shear stress profiles were obtained at a number of locations behind the downstream machine. Their measurements were compared with the predictions of a model that is also presented in [156], and obtained a reasonable agreement. Smith and Taylor [156] observed that the maximum turbulence intensity in the far wake is located above the turbine axis, as can be seen in Fig. 35. This is probably because the turbulence in the far wake “remembers” how it was originated in the “near wake”. In the near wake, turbulence production is more important in the upper part of the shear layer where the velocity gradients are more intense, and the eddy viscosity of the ambient flow is larger. As can be observed in this and other wind tunnel experiments [156,170,164,174–176] there is a well defined annular peak of turbulence intensity in this cylindrical shear layer, with its highest values in the upper part. This is also observed in field experiments

and numerical models [156,177]. Crespo and Hernández [157] gave a theoretical estimation of this peak, and compared it with the previously mentioned experimental results. The added turbulent kinetic energy turned out to be $\Delta k = \Delta u^2/8$, where Δk is the turbulent kinetic energy created in the shear layer and Δu is the velocity deficit in the near wake. Within the same research program as Smith [173], Hassan et al. [176] performed similar experiments, but also included larger wind farms with different lay-outs, some of them with 15 turbines. They were the first ones to measure wind loads in wakes in a wind tunnel. They found a substantial increase in the dynamic loads when the turbines were within the array; that is to be expected because of the higher turbulence; however, they found the surprising result that the loads for some downstream rows are smaller than in upstream rows, where supposedly wake effects are more intense. Another interesting result, also confirmed by field experiments, is that highest loads do not occur when the rotor is on the wake centre, but when is only partially immersed.

A series of well planned experiments were carried out by Talmon [178,167] that used a moving model in a simulated atmospheric boundary layer; he investigated the effect of the tower, nacelle and floor of the wind tunnel on the wake. He found a downshift of the maximum velocity deficit, oppositely to what happens with the maximum turbulence intensity. These experiments have been used by Luken and Vermeulen [179] and Crespo et al. [180] to check the validity of their wake models. In the numerical calculations of Crespo et al. [180], it is shown that this downshift is mainly due to the shear of the incoming flow and the presence of the ground. Comparison of the measurements and model results is shown in Fig. 38.

The superposition of several wakes was studied by Smith and Taylor [156], who found that the wake of the downstream machine recovers more rapidly than the one upstream so that, at the same relative position, the velocity deficit is smaller in the downstream machine wake. This surprising behaviour may be explained by the enhanced momentum diffusion due to the high turbulence levels and shear stress profiles generated by the upstream machine, that leads to a faster recovery in the downstream machine. What is usually found when there is superposition of wakes is that the rate of decrease of wind velocity is smaller after crossing several rows of wind turbines, and tends to reach an equilibrium value, as can be seen in Ross and Ainslie [39], and in field experiments and numerical models that will be examined in the following sections.

The wake behaviour in complex terrain was studied by Taylor and Smith [181] in the wind tunnel. The scale was 1/1000, and the turbine was located at several positions in a flat-topped hill 0.3 m high, and 0.6 m long. A static simulator of 72 mm diameter was used for the

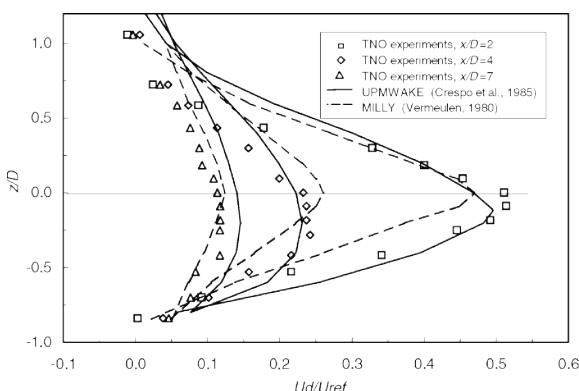


Fig. 38. Vertical distribution of maximum dimensionless velocity deficit along the wake as a function of vertical distance divided by turbine diameter for several downstream sections. Comparison of wind tunnel measurements from Vermeulen [179], and results of wake models, UPMWAKE from Crespo [180], and MILLY from Vermeulen [169].

turbine, its thrust coefficient was 0.78, including the effect of the supporting stem. The incoming flow simulates the logarithmic velocity distribution with a surface roughness of 0.2 mm and a turbulence intensity of 10.5%. Cross hot-wire anemometers were used for the wake measurements, and two mean and turbulent velocities were recorded at each point. They found that the influence of the terrain may be both significant and subtle. When the turbine is in the upstream side of the hill, there is a downwards displacement of the point of maximum velocity deficit, accompanied by a significant broadening of the lower part of the wake. As it was mentioned before this downshift also happens in flat terrain, as can be seen in [179,180], although the effect is more important in this case, probably due to the convergence of the stream lines. They also found that the wake of a turbine located upstream may also inhibit separation in the downstream side of the hill. Stefanatos et al. [182,183] and Helmis et al. [158] also studied the interaction between wake and terrain, both in wind tunnel and in large-scale tests, and from their results obtained some guidelines for the modellisation of this interaction.

Within an European project, Tindal et al. [184] have carried out wind tunnel wake studies, similar to those quoted before [156,176], that have been complemented with numerical calculations and field experiments in the Sexbierum and Nørrekaer Enge II wind farms, that will be described in the next section.

5.2. Field experiments

Relevant field experiments with a single turbine have first been made in the Näsudden turbine by Höglström

et al. [159], that is a 2 MW turbine of 75 m diameter. Measurements were made with a high resolution SODAR (Sonic detection and ranging) at 2D–4D downstream from the turbine, which enabled to carry out detailed studies of both mean velocity and turbulence intensity in the wake. Additional data were obtained from a tower of 145 m height, located 3D downstream, instrumented to measure velocity and temperature at six different levels, and special equipment (wind vane three axial hot film probe) to measure turbulence characteristics at three levels. These measurements, at a sampling rate of 20 Hz, could provide all turbulence moments and spectra. At a distance of 10.5 D measurements were taken with Tala Kites, that provided velocity deficit and longitudinal turbulence intensity at the centre line. A similar, although less ambitious project, was carried out in Goodnoe Hills [185] with the MOD-2 machine of 91.4 m diameter. Nevertheless, in this case the data was more difficult to interpret because of the complex orography. It was found that the wake deficit dissipated more rapidly than predicted by wind tunnel experiments, this has also been observed by Höglström et al. [159], although in this case this result may be due to the orography.

Earlier work on this subject, involving several turbines, was related to the Nibe project, and measurements were made by Taylor et al. [186–188] and Højstrup [189]. The installation consisted of two machines of 40 m diameter, located 200 m apart, and four measurement towers located on the intermachine axis. One tower has five anemometers and the others seven anemometers at different heights. Average flow properties and turbulence characteristics, both turbulence spectra and turbulence intensity, were measured. A project of similar characteristics, with two turbines of 20 m diameter was that of Burglar Hill [190,191]. Højstrup [192] made also measurements of turbulence characteristics in the Tændpipe wind farm, that consists of 35 machines of 75 kW each. He used both cup and 3D sonic anemometers, the latter ones for high frequency turbulence measurements. Højstrup also performed measurements [172] in the Nørrekaer Enge II wind turbine array, that consists of 42 Nordtank turbines of 300 kW separated 6–8D. He found that the spectral distribution of increase in turbulence corresponded to a band of frequencies whose scale is of the order of the width of the wake, as in the wind tunnel experiments of Vermeulen and Bultjes [162]. For some frequencies there may be even a decrease in turbulence. This may be because the wind turbine is capable of responding to low frequency fluctuations of wind speed and extracts energy from the wind in the low frequency (large-scale) range [189]. As discussed previously, a shift of the wake spectrum towards higher frequencies has also been observed in wind tunnel experiments [162]. Nevertheless, this tendency may be reversed for wind speeds higher

than that corresponding to the maximum power coefficient, as measured by Papadopoulos et al. [193], that made measurements in the wake of a single turbine in the Samos Island wind farm. Velocity spectra were also measured in the offshore Vindeby wind farm [194], that consists of 11 machines of 450 kW which are arranged in two rows, each machine and each row separated by approximately 8D. Two instrumented masts provide measurements of ambient and wake-flow parameters. The geometry of the wind farm and the instrumentation allowed for both single and multiple-wake measurements. It was observed that there is a great variation in the length scales of turbulence in the wake region, probably because atmospheric stability, and in particular the length scale in the wake is found to be much smaller than in free flow. Tindal et al. [184] also report, from wind tunnel experiments, that in the near wake the turbulence length scale is reduced to a quarter of the free stream value. Højstrup and Courtney [195], based on data from several wind farms, indicate that the shear layers in the wake create turbulence at much smaller length scales than those seen in free turbulence. Probably what is observed is that the turbulence length scale in the wake is related to the wake width, as discussed previously in the wind tunnel experiments of Vermeulen and Bultjes [162].

Kline [196] made measurements in a Howden wind farm, in Altamont Pass in California, in a cluster of 75 turbines of 33 m diameter. Emphasis was put in estimating characteristics of gusts in wakes. Also, they report measurements of horizontal shear at 2D (diameters) and 6D downstream. Other measurements of velocities and turbulence intensities were also made in Altamont Pass in California [197,198] for clusters of smaller wind turbines.

The Zeebrugge [199,200] wind farm became operational in 1987 and has 23 turbines of 22 m diameter. Two fully equipped wind masts are installed so that unperturbed wind conditions could be measured. Recordings of 10 min data sets, including wind velocity and direction, turbulence intensity, and power output were obtained. The main purpose of the research was to investigate power production and compare the measurements with the results of different models. The effect of other obstacles, such as LNG tanks in the harbour, had to be included in the analysis.

In the Vindeby wind farm, within the ENDOW (Efficient Development of Offshore Wind Farms) project, measurements have been made using SODAR instrumentation mounted on a boat [201]. This is an interesting method to complement measurements in wakes performed with fixed meteorological masts.

5.2.1. Fatigue and loads

The most important structural effect on a wind turbine which is in the wake of a neighbouring machine

is fatigue, that is due to the combined effect of increased turbulence, wind speed deficit and shear, and changes in turbulence structure that cause dynamic loading, which may excite the wind turbine structure. There is a need for revision of the standards on wind turbine design and safety, to adequately account for increased fatigue loading in wind turbine clusters; this issue has been addressed by Frandsen and Thøgersen [202]. Fatigue in wind turbine clusters has already been reviewed in [203], so that previous efforts will not be considered in much detail. Earlier work on this subject was made in the Nibe project [186,187] where special emphasis was put in measuring the wake induced loads, because of its implication in the fatigue life of the machine. Other earlier measurements of loads were made by Vølund [204] and Stiesdal [205], for machines that were 2 to 3D apart. They found increases of the standard deviation of the flapwise bending moment of the order of 100% relative to the unobstructed case. Loads were largest when the machine was exposed to half-wake conditions. Stiesdal [205] introduced the concept of equivalent load, that is the amplitude of a sinusoidal load with a fixed frequency that would generate the same fatigue damage as the actual (random) load; this concept provides a more precise fatigue measurement than the standard deviation. Measurements have been made on one wind turbine in the experimental Alsvik wind farm in Sweden [206], which has four machines sited so that the instrumented unit is exposed to 5D, 7D or 9.5D single-wake loads, depending on wind direction. The terrain is smooth and the ambient turbulence low. The wind farm layout is unique in offering many experimental possibilities. It was found that under full-wake conditions the equivalent load is increased by 10% at 9.5D and up to 45% at 5D. Their conclusion is that for low roughness and low ambient turbulence sites, as occur in offshore wind farms, the wake effects are very important for wind turbine loads and fatigue. This is probably due to the fact that under these conditions wakes are more persistent, because diffusion due to ambient turbulence is smaller in the sea. Similar results were reported by Thomsen et al. [207] in the Kappel wind farm in Denmark, that consists of 24 units of 400 kW, sited in a row on a westerly shoreline, with 3.7D separations. However, in a later paper Thomsen and Sørensen [208] observe the same relative increase in fatigue loads for an offshore wind farm and a land site wind farm. Frandsen and Christensen [209] made measurements in the large Nørrekaer Enge II wind turbine array in Denmark. Two turbines in opposite corners of the wind farm were instrumented to measure stresses in towers and blades. There was a clear increase in the standard deviation of the fluctuating load when the instrumented machine was in the direct wake of a neighbouring machine, although the integrated effect of wake and non-wake operation was significantly smaller. Frandsen and Thomsen [210]

carried out similar measurements in the Danish offshore Vindeby wind farm. Data, including equivalent loads, were recorded for two years. Despite the fairly large spacing between wind turbines, the fatigue load increase in the wake is significant, about 80%. The data obtained for several wind directions demonstrate that there is no appreciable difference between single and multiple-wake loads. Further measurements of fluctuating loads in the Vindeby wind farm were reported by Thomsen and Sørensen [208], that give measured values of the power spectrum density function of flapwise bending moment, both in free flow and in wakes, and compare them with the results of an aeroelastic code. The Sexbierum wind farm in the Netherlands consists of 18 units of 300 kW, placed in three rows, each with six machines [211]. The machines are spaced 5 or 10D apart and the rows are separated by 8D. Six meteorological towers provided information on flow characteristics. As in the Vindeby wind farm, it was found that equivalent fatigue loads under single and multiple-wake conditions were very similar.

5.2.2. Anisotropy

The anisotropy of turbulence characteristics in wakes was measured by Cleijne [212] in the Sexbierum wind farm. The six components of the symmetric turbulence stress tensor were measured. The shear stress turns out to behave similarly to the velocity shear, indicating, at least qualitatively, the validity of the eddy viscosity assumption; similar results were obtained in wind tunnel experiments by Smith [173]. In general the turbulence in the wake seems to be more isotropic than in the outside flow, although, locally, there are some peaks of turbulence intensity of the component in the wind direction, that are less intense for the turbulence intensities in the other directions. These peaks occur where the gradient of the average velocity is largest. In Figs. 39 and 40 some of these results and its comparison with the UPM-ANIWAKE model proposed by Gómez-Elvira and Crespo [213] can be observed. In Fig. 39 are given the values of the turbulence intensity in the average flow direction, $(\overline{u'^2})^{1/2}/u_0$ and vertical direction, $(\overline{w'^2})^{1/2}/u_0$. The other component of the turbulence stress tensor that is not represented, $(\overline{v'^2})^{1/2}$, has values in between them. The peaks can be clearly observed in the shear layer, and the anisotropy in these peaks is smaller than in the unperturbed flow outside the wake. The turbulence is even more isotropic in the center of the wake, where all the turbulence components, including the horizontal one not represented, have approximately the same value. The longitudinal turbulence intensity decreases below its ambient value, and the vertical one increases, so that both become equal in the center of the near wake. In Fig. 40 is presented the non-diagonal components of the turbulence stress tensor, $(\overline{u'v'})^{1/2}$, corresponding to the correlation of the fluctuations of

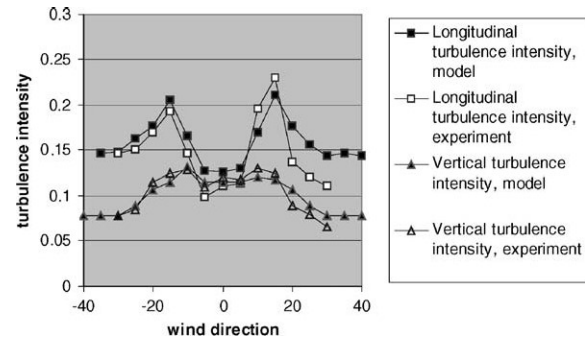


Fig. 39. Turbulence intensity in the average flow direction, $(\overline{u'^2})^{1/2}/u_0$ and vertical direction, $(\overline{w'^2})^{1/2}/u_0$, at a downstream distance of 2.5D, in a horizontal plane. Comparison of measurements in the Sexbierum wind farm from [212], and UPM-ANIWAKE model from [213].

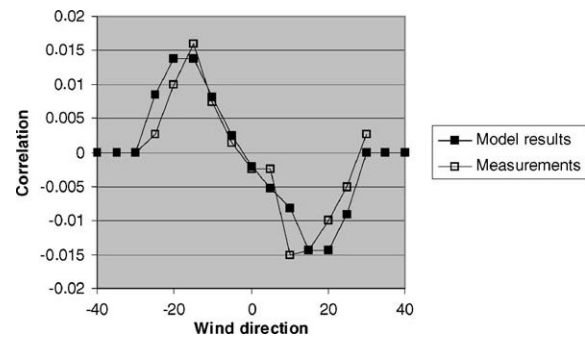


Fig. 40. Correlation of the fluctuations of the two horizontal components of velocity, $(\overline{u'v'})^{1/2}/u_0$, at a downstream distance of 2.5D, in a horizontal plane. Comparison of measurements in the Sexbierum wind farm from [212], and UPM-ANIWAKE model from [213].

the two horizontal components of velocity; it also has peak values in the shear layer, and is zero in the wake centre.

5.2.3. Atmospheric stability

Another important aspect is the influence of atmospheric stability on wake behaviour. Some interesting experimental results have been presented by Magnusson [214] and Magnusson and Smedman [177]. They performed experiments in the Alsvik wind farm and measured at 4.2D, 6.1D and 9.6D downstream of a machine. They found that, for unstable stratification with Richardson number (Ri) values smaller than -0.05 , the velocity deficit is independent of stability, while it increases linearly with Ri in the interval $-0.05 < Ri < 0.05$; this is due to the fact that in a stable atmosphere there is less diffusion of the velocity deficit. More recently they found [215] that for $0.25 < Ri$ there is

a tendency for the deficit to decrease, which would indicate more effective mixing.

5.2.4. Coherence

Coherence is another magnitude of interest, and is defined as the absolute value of the normalized two-point spectrum. It represents the degree to which two wind speeds at points separated in space are alike in their time histories. It could be useful to estimate the duration of a gust whose size should be large enough to engulf a rotor, and also to translate the spectra from an Eulerian frame to a rotating frame as seen by the turbine blades. Højstrup [172] has made measurements in the Nørrekaer Enge II wind farm, of the spectral coherence, both vertical and lateral, in wakes of wind turbines. He found that there is a small influence of the wake on vertical coherence, and that the lateral coherence was only modified in the near wake. Nevertheless, this result may be influenced by the fact that in these experiments the distances between the two points were small compared to the size of the wake.

6. Far wake modelling

In this section the numerical research on the far wake will be presented. Much of it has already been reviewed by Crespo et al. [203], so that previous contributions in this field will not be examined in much detail. The first subsection will be dedicated to individual wakes in flat terrain, that are easy to characterize with few parameters, and provide information of basic interest that can be easily arranged. However, the usual situation of practical interest, that will be discussed next, is that many wind turbines are located in a wind farm with irregular terrain, where the different wakes interact.

6.1. Individual wakes

6.1.1. Kinematic models

The first approach to study wind–turbine wakes was introduced in a seminal paper by Lissaman [216] with a so-called kinematic model. Kinematic models are based on self-similar velocity deficit profiles obtained from experimental and theoretical work on co-flowing jets. The wake description starts after the wake has expanded; and are assigned different types of transverse velocity profiles for the near, transition and far wake regions. Lissaman [216] and Voutsinas et al. [217] used velocity profiles obtained from models on co-flowing jets by Abramovich [218]. Vermeulen [169] used a Gaussian type of profile quite similar to that of Abramovich [218], and Katic et al. [219] simplified the problem further and assumed a top-hat profile everywhere. The reference value of the velocity deficit is usually obtained from global momentum conservation, using as input the

thrust coefficient of the machine. The wake growth is due to the added effects of the ambient turbulence and the turbulence created by the shear in the wake. Vermeulen [169] added another term: the turbulence created by the turbine itself. Katic et al. [219] simply assumed that the wake radius increases linearly with downstream distance; the proportionality constant must be adjusted by comparison with experiments. The ground effect is simulated by imaging techniques. Lissaman [216] included a symmetrical turbine and added the velocity deficits of both the real and image turbine, so that drag conservation is satisfied. Crespo et al. [220] use an antisymmetric wake so that velocity deficits are subtracted and give zero perturbation at the ground. The differences in the results are not important, and it is not clear which procedure is more appropriate.

6.1.2. Field models

The field models follow a different approach and calculate the flow magnitudes at every point of the flow field. The earlier models assumed axial symmetry, such as the simple model proposed by Sforza et al. [221], that used the linearized momentum equation in the main flow direction, with constant advective velocity and a constant eddy diffusivity. They made small-scale experiments, and the agreement was reasonable, considering the simplicity of the model. A more complete parabolic model, EVMOD, was developed by Ainslie [222,223] assuming an eddy viscosity method for turbulence closure. The eddy viscosity is represented by a simple analytical form based on Prandtl's free shear layer model, but which also includes a contribution from ambient turbulence. This eddy viscosity is an average value over a cross-section. At small downstream distances, the eddy viscosity is modified by an empirical filter function to account for the lack of equilibrium between the mean velocity field and the developing turbulence field. Several constants appear in the problem, that are adjusted by comparison with particular experiments. The model is fairly simple and gives reasonable results when compared with wind tunnel experiments [179,224]. For large-scale experiments, the results are corrected by taking into account meandering effects. Nevertheless, some aspects such as the downshift of the wake centreline, or the upward displacement of the maximum turbulence intensity, can never be well predicted by models with axial symmetry. To reproduce such effects, models which retain three-dimensional effects are needed.

6.1.3. Boundary layer wake models

Crespo et al. [220,225] developed the UPMWAKE model in which the wind turbine is supposed to be immersed in a nonuniform basic flow corresponding to the surface layer of the atmospheric boundary layer. The properties of the nonuniform incident flow over the

wind turbine are modelled by taking into account atmospheric stability, given by the Monin–Obukhov length, and the surface roughness. The modelling of the turbulent transport terms is based on the k – ε method for the closure of the turbulent flow equations, previously presented. Finite-difference methods were used in the discretization of the equations. A parabolic approximation was made and the equations were solved numerically by using an alternate-direction implicit (ADI) method. The developed wake model is three-dimensional and pressure variations in the cross-section have to be retained in order to calculate transverse velocities. Crespo and Hernández [226,225] and Crespo et al. [180,227] compared UPMWAKE results with the results of wind-tunnel experiments obtained by Luken et al. [224] and those of field experiments using full-scale machines [186]. The code can predict effects such as the downward tilt of the wake centreline, as shown in Fig. 38, the upward displacement of the point of maximum added turbulence kinetic energy, as shown in Fig. 35, or the different vertical and horizontal growths of the wake width.

Another approach was followed by Taylor [228] and Liu et al. [229], that retained Coriolis forces and assumed that the pressure gradients were given by the geostrophic wind. However, this assumption cannot be justified because the length scale of the wake is not sufficiently large for the Coriolis forces to play a dominant role; indeed, they can be neglected, and the pressure field will be that resulting from the momentum conservation in the wake. If a parabolic approximation is made, pressure variations across the wake can be neglected in the momentum equation for the main flow direction, but not for the momentum components in the transverse direction, particularly when there is neither axial nor two-dimensional symmetry. Taylor's model [228] was two-dimensional, and the equations were linearized around a basic flow. Liu et al.'s model [229] was three-dimensional, and included atmospheric stability effects.

Smith and Taylor [156] and, in more detail, Taylor [230] presented a non-symmetric two-equation model that is in many ways similar to the three-equation model of Crespo et al. [220]. They neglected transverse velocities and just solve the momentum equation in the axial direction. To model the turbulent viscosity they use a k – L method, where the turbulent length scale, L , is related to the width of the wake. The comparison with their wind-tunnel experimental results is very good, as can be seen in Fig. 35, although a comparison with full-scale Nibe measurements showed that the model overestimates the values of the velocity deficit. They attributed this discrepancy to meandering and obtained better agreement when they corrected for this effect using the method proposed by Ainslie [223].

Based on the model developed by Ainslie [223], the company Garrad and Hassan has developed the code EVFARM, described by Adams and Quarton [231]. The code incorporates two alternative semi-empirical models to calculate wake turbulence. Adams and Quarton [231] use both EVFARM and UPMWAKE codes in combination with machine load predictive tools to provide a method for fatigue load prediction. As part of this study, a comprehensive validation of both codes is made using the wind tunnel measurements of Hassan [232]. A better agreement with experiments is found if a downstream displacement of the origin is considered. In the initial region of the wake some important discrepancies were also observed between the results of UPMWAKE and the Nibe measurements published by Taylor et al. [186]. On the other hand, by eliminating the boundary layer approximation used in UPMWAKE, Crespo et al. [227] proposed an elliptic model to deal simultaneously with the axial pressure gradients and diffusion effects by retaining both the axial and transverse diffusion terms. Their model therefore describes both the evolution of the expansion region and the diffusion processes in the near wake. No fundamental differences between the results of the elliptic and parabolic models were found, and displacement of the origin was apparently not necessary. Another reason for the discrepancies observed between models and experiments in the near wake may be the uncertainty involved in the radial distribution of the initial velocity deficit, that has been studied by several authors, [230,233–235] and is discussed in more detail in the first part of this review. Schepers [236] found that, by using a Gaussian profile for the initial velocity deficit, a significative improvement of the agreement with experimental results is obtained.

6.1.4. Hybrid models

An alternative approach that requires less computing capacity is the multi-parametric wake model of Voutsinas et al. [237,238], which was further developed by Cleijne et al. [235]. This model divides the wake into the rotor region, the near wake region and the far wake region, and applies a vortex particle method in the rotor region, a field model in the near wake region, and, in the far wake region, explicit self-similar expressions similar to those used in the kinematic models. Different assumptions are made to match the different regions. The method was partially successful in simulating the experimental results of the Nibe turbines given in Taylor [188]. Later, Magnusson et al. [239] applied the model to reproduce the experimental results of the Alsvik wind farm. Explicit expressions for wake characteristics obtained from this work were later applied to study the noise emissions from wind farms [240].

All these models use a closure scheme, based on zero, one or two equation models, to calculate the turbulence transport terms, and assume an isotropic turbulence

field. Transport equations for the Reynolds stresses have only been used occasionally. Anson et al. [241] used a Reynolds-stress turbulence model based on the commercial code PHOENICS and obtained reasonable results. More recently Gómez-Elvira and Crespo [213] have extended UPMWAKE by using an explicit algebraic model for the components of the turbulent stress tensor. The constants of the new model, UPM-ANIWAKE, have been adjusted, so that it will reproduce the logarithmic layer of the basic flow and the corresponding stress tensor. The new model has a low computational cost, and its results are compared to experimental data from the Sexbierum wind farm [112], as can be seen in Figs. 39 and 40, previously commented, and a reasonable agreement is obtained.

6.2. Wind farm wake models

6.2.1. Single wake superposition

A wind farm consists of many wind turbines whose wakes can interact, and whose turbines may be affected by the wakes of several machines located upstream. Wind farm codes usually rely on the results of single wake calculations, and make superposition assumptions to take into account the combined effect of different wakes. The linear superposition of the perturbations created by wakes of different machines in a wind farm model was first used by Lissaman [216] in a classical paper, although this assumption fails for large perturbations as it overestimates velocity deficits and could lead to the absurd result of negative velocities when many wakes superimpose. Instead, Katic et al. [219] assumed linear superposition of the squares of the velocity deficits. In this case, the cumulative effect, when there are many wakes, will be smaller than that calculated for linear superposition, and, in general, this assumption provides better agreement with experimental results than the linear superposition, although, apparently, there is no physical reason for it. The corresponding code, named PARK, was applied by Beyer et al. [242] for the optimization of wind farm configurations using genetic algorithms. As already mentioned, Smith and Taylor [156] found, for a particular experimental configuration of two machines in a row, that the wake velocity of the downstream machine recovers more rapidly than the one upstream. By making a number of crude assumptions concerning the momentum transfer within the downstream wake that is imbedded in the upstream wake, Smith and Taylor [156] were able to formulate a semi-empirical superposition law that works quite well. However, it is cumbersome and can only be applied for the interaction of the wakes of two turbines in a row. When there are many turbines in a line it has been observed experimentally [200] that while the first turbine produces full power, there is a significant decrease of power in the second turbine, with practically no further

loss in successive machines. Based on these observations, and on the results of the calculations of Crespo et al. [227], Van Leuven [200] assumed in his farm model (WINDPARK) that a given turbine is only affected by the wake of the closest upstream turbine, obtaining good agreement in comparison with measurements made at the Zeebrugge wind farm.

6.2.2. Elliptic wake models

Crespo et al. [227] applied an elliptic model for studying the interaction of the wakes from two turbines in two configurations: abreast and in a line. There was good agreement with experimental results, and, when other superposition assumptions were compared, it was found that the linear superposition worked well for the two machines abreast, in which velocity deficits in the interference region are small. However, for the two turbines placed in a row the linear superposition overestimated the velocity deficit, as was to be expected. Recently, this model has been improved by Sotiropoulos et al. [243] by a more detailed analysis of the rotor and inclusion of terrain effects; the results are in fair agreement with measurements in the Alsvik wind farm [239] and in wind tunnel. When the results of the elliptic model [227] are considered, it can be observed that the truly elliptic effects, such as axial pressure variations, only occur very close to the turbine, so that the parabolic approximation may be a suitable approach for studying wake interactions over most of the region where this interaction occurs. Moreover, to extend the fully elliptic code to a wind farm consisting of many machines, besides consuming a lot of calculation time, would require very powerful computers and would therefore be of little practical interest for modelling wind farms.

6.2.3. Parabolic wake models

Because of the above, Crespo et al. [244] have developed a code, UPMPARK, extending the parabolic UPMWAKE code for a single wake to the case of a park with many machines. No assumptions are required regarding the type of superposition or the type of wake to be used, as all the wakes and their interactions are effectively calculated by the code. In UPMPARK, the conservation equations solved are the same as those for the single wake code, UPMWAKE, as specified in Crespo and Hernández [225], and turbulence is closed using a $k-\epsilon$ model. Adams and Quarton [231] extended the UPMWAKE model to wind farms using a procedure quite similar to that of UPMPARK; this extended code has been incorporated in a wind farm design support tool, named FYNDFARM (Fatigue Yield Noise Design Farm) [245].

Usually wind farm models make the assumption that the terrain is flat and that the unperturbed wind velocity is uniform, an assumption which is not reasonable in

many cases of interest since, as is well known, terrain irregularities can be used to enhance or concentrate wind power. For terrains that are moderately complex, the simple procedure of adding the velocity perturbations of the wake and terrain should give an approximate flow field; this or equivalent procedures were applied in [226,231,200]. In the Monteahumada wind farm the velocity irregularities of the terrain and the velocity deficit created by a single wake are both of a similar order of magnitude; from its analysis it is shown, [246], that, for a moderately irregular terrain, the linear superposition of wake and terrain effects gives reasonable results. More elaborated models to take into account terrain effect on wakes are proposed by Voutsinas et al. [247], Stefanatos et al. [182], Hemon et al. [248], and Migoya et al. [249].

6.2.4. CFD code calculations

Numerical calculations using commercial CFD codes were made by several authors, [241,250] to study wake and terrain interaction for simple configurations, but their extension to wind farms of typical size will be computationally expensive. More recently, Chaviaropoulos and Douvikas, [251], and Ivanova and Nadyozhina, [252], have developed their own in-house CFD methods that deal simultaneously with terrain and wake effects. In [252] the turbines are considered as distributed roughness elements; this approach will be discussed later. In [251] a $k-\omega$ model for closure was used, the numerical results were compared with experimental measurements, and the accuracy of the simulation is fair. The method was applied to sets of one and two turbines and also seems to be computationally expensive for conventional wind farms.

As mentioned previously Taylor and Smith [181], Stefanatos et al. [182,183], and Helmis et al. [158] gave some guidelines for the modelling of the terrain-wake interaction.

6.2.5. Offshore wind farm wakes

A related problem arises in offshore wind farms where, when the wind blows from land to sea, there is an internal boundary layer, whose development is superposed on that of the wakes, as mentioned by Crespo and Gómez [253]. As the surface roughness of the sea is usually much smaller than the corresponding roughness on land, it is to be expected that wind velocity will be greater and turbulence intensities lower than for equivalent inland stations. Consequently, turbulent diffusion of the wake will also be lower and wake effects will probably be more persistent downstream. Wake effects in offshore wind farms obtained from both experiments and numerical models are reported by Frandsen et al. [194], Crespo et al. [254,243] and their effect on fatigue loading by Frandsen [255]. Recently, within the ENDOW project, the performance of several

wake models in offshore wind farms has been evaluated [256]. A total of seven models have been proposed within the ENDOW project: an axisymmetric semi-analytical engineering model (Risø), an advanced code based on computational fluid dynamics, that is coupled to an aeroelastic model (Risø), an analytical model based on Taylor's hypothesis for closure (Uppsala University), two axisymmetric models based on eddy-viscosity assumption for turbulence closure (Garrad Hassan, and Oldenburg University), a fully elliptic 3D turbulent Navier–Stokes model with $k-\epsilon$ assumption for closure (Robert Gordon University, RGU), and a modification of UPMWAKE made by ECN (Netherlands Energy Research Foundation) [236]. Comparisons were made of the results of the different models and with experimental results in Vindeby and Bockstigen wind farms. In all cases large discrepancies appear in the near wake region, see Figs. 41 and 42.

Compared to the Vindeby experimental results, all the models overestimate the wake effects in the case of low ambient turbulence (6%), and give acceptable results in the case of higher ambient turbulence (8%). The 3D models, ECN and RGU, predict downward shift of the maximum velocity deficit, that is also confirmed by experimental results, as previously mentioned, see Fig. 38. The superposition of several wakes in double and quintuple wake cases is being also examined within the ENDOW project [257], and preliminary results point out the importance of including correct values of the ambient turbulence intensity. Another issue addressed by ENDOW, is how to link wake models with atmospheric boundary layer models; this is also in its

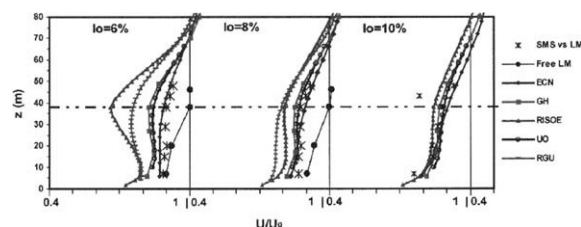


Fig. 41. Example results from the ENDOW project: cross wind profiles in vertical direction (from [256]).

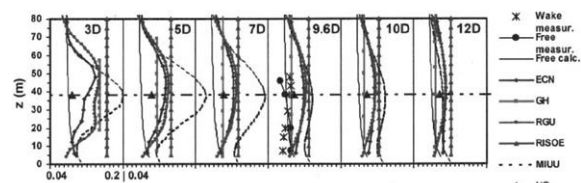


Fig. 42. Example results from the ENDOW project: turbulence in the wake (from [256]).

preliminary stages, and it does not seem to contemplate the superposition of wake and local terrain effects yet [258]. This linking provides the input needed for the wake models, assuming that the calculated atmospheric conditions are uniform along the wind farm.

6.2.6. Generic wind farm wake models

Another approach to model wind farms is to consider that the turbines behave as distributed roughness elements. Several models were proposed by Newman [259] and Bossanyi [260]. They assumed a logarithmic wind profile for the unperturbed wind, which includes ground roughness as a parameter. The presence of the turbines increases the value of the roughness. Frandsen [261] gave an explicit expression relating the artificial surface roughness to the wind turbine characteristics and its spacing within the wind farm.

Recently, the distributed roughness model has been used by Crespo et al. [262] to estimate how the large offshore wind farms may change the local wind climate, and how in turn this change of the climate will affect the local behaviour of the wind farm. In a first approach, the large wind farm is simulated by an artificial roughness as proposed in [261]. An internal boundary layer is considered that starts developing at the leading edge of the farm until it reaches, sufficiently far downstream (if the wind farm is large enough), the top of the planetary boundary layer, after that a new equilibrium region is reached. This will occur in a large distance, so that presumably, most of the wind farm will be immersed in the developing internal boundary layer. From the calculation of the internal boundary layer, the flow conditions are obtained at a certain reference height, these are then used as boundary conditions for UPMPARK. In [262] a large wind farm has been considered, that has 384 turbines of 1.5 MW rated power each; the evolution of the local turbulence intensity at hub height, as the distance from the leading edge increases, is calculated, and is presented in Fig. 43. A comparison is made with an equilibrium value predicted by Frandsen and Thogersen [202], that will be presented later in Eq. (30).

A different approach was used by Hegberg [263] that analysed the equilibrium region by establishing a global balance of Coriolis, pressure and drag forces.

Recent work on local wind climate, within and downwind of large offshore wind turbine clusters, was presented in a meeting for experts at the Risø Laboratory, that is reviewed by Frandsen and Barthelmie [264]. In this meeting, it was pointed out that the new understanding of resistive flows can be obtained from other areas of fluid dynamics, such as flow behind buildings and in forest canopies [265].

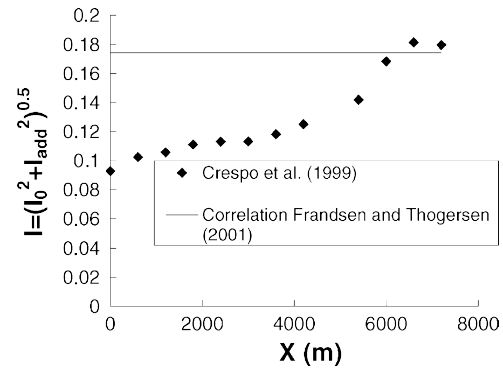


Fig. 43. Local turbulence intensity at hub height, as function of the distance from the leading edge of the wind farm, from [262]. Comparison with an analytical prediction for equilibrium conditions in an infinitely large wind farm, from [202], see Eq. (30).

7. Far wake: engineering expressions

7.1. Velocity deficit

In many cases it is of interest for the designer to have, as an alternative to numerical models, analytical expressions which can estimate the order of magnitude and the tendencies of the most important parameters characterising wake evolution. Regressions or correlations of this type were obtained by different authors to describe single wake behaviour, [226,224,159,266,215], for the velocity deficit and the width of the wake. For the velocity deficit in the far wake, these correlations are usually of the type:

$$\frac{\Delta V}{V_{\text{hub}}} = A \left(\frac{D}{x} \right)^n, \quad (23)$$

where V_{hub} is the incident wind velocity at hub height, x is the downstream distance, D the wind-turbine radius, and A and n are constants. In some cases, to extend the range of validity of this equation to smaller values of x , its origin is displaced. The constant A will depend on turbine characteristics, fundamentally on the thrust coefficient, C_T or the induced velocity factor, a , and will increase with either of them. These constants are in the range $1 < A < 3$, and $0.75 < n < 1.25$, respectively. If we consider an axisymmetric wake we can apply classical results, see for example the book of Schlichting [267]. For the case of a turbulent wake that is diffusing with zero ambient turbulence, $n = 2/3$, [268], and for a laminar wake, or equivalently when diffusion is controlled by a constant ambient turbulent diffusivity, $n = 1$.

Instead of using the non-dimensional distance, x/D , Magnusson and Smedman, [266,215], expressed wake diffusion as a function of the transport time $t = x/V_{\text{hub}}$

made dimensionless with t_0 , the transport time where the near wake ends. Their correlation takes the form

$$\frac{\Delta V}{V_{\text{hub}}} = C_2 \ln\left(\frac{t_0}{t}\right) + C_T, \quad (24)$$

valid for $t > t_0$, and for t_0 in neutral atmosphere they give

$$t_0 = C_1 \frac{1}{f} \ln\left(\frac{H}{z_0}\right) \frac{D}{2H}, \quad (25)$$

where H is the turbine height, z_0 is the surface roughness of the ground, f is the rotational frequency of the turbine, and C_1 and C_2 are constants, taken respectively equal to 1 and 0,4, in [215].

7.2. Turbulence intensity

Correlations for turbulence intensity in the far wake have been given in [224,162,159,161,171,157,266,268]. Crespo and Hernández [157,171], give the following expression for the added turbulence intensity, created by the turbine:

$$\Delta I = 0.73a^{0.83} I_{\infty}^{-0.0325} \left(\frac{D}{x}\right)^{0.32}. \quad (26)$$

The turbulence intensity, I , is defined as the ratio of the standard deviation of the wind velocity in the average wind direction, divided by the average wind velocity. It is assumed that the wind turbine creates an additional turbulent kinetic energy that should be added to the ambient one, consequently, ΔI will be,

$$\Delta I = \sqrt{I^2 - I_{\infty}^2}, \quad (27)$$

where I_{∞} is the ambient turbulence intensity. This expression was obtained by fitting with the numerical results of UPMWAKE, and was validated by comparison with experimental results, both of wind tunnel and field experiments (many of them compiled by Quarton [161]). A similar expression was proposed in [161], obtained by fitting with experimental results:

$$\Delta I = 4.8C_T^{0.7} I_{\infty}^{0.68} \left(\frac{x_N}{x}\right)^{0.57} \quad (28)$$

where the drag coefficient, C_T , has been used instead of the induced velocity factor a , and the diameter has been substituted by the near wake length, x_N , that is of the order of 1D–3D. Frandsen and Thøgersen [202] proposed the following correlation based on measurements:

$$\Delta I = \frac{1}{1.5 + 0.3(x/D)\sqrt{V_{\text{hub}}}}, \quad (29)$$

where V_{hub} is related to C_T . The decay with downstream distance is smaller in Eq. (26), $x^{-0.32}$, than in Eq. (28), $x^{-0.57}$ and in Eq. (29), that for large values of x , will be like x^{-1} . In [159] a decay like $x^{-0.5}$ is obtained. In [268] it

is observed that the behaviour should be like $x^{-1/3}$; this corresponds to the classical situation of a wake developing in an ambient with no turbulence [267]. If only field experiments are used, in Eq. (28) the exponent will be 0.37, whereas, from wind tunnel experiments made at TNO [160], the behaviour is estimated to be like $x^{-0.7}$. In any case it should be noticed that the decay of turbulence intensity, ΔI , is slower than the decay of the velocity deficit, ΔV . Frandsen [269] has plotted the three correlations: (26), (28), and (29), with different coefficients, in order to fit to some experimental results. These are shown in Fig. 44. It can be seen that the agreement of the correlation of Crespo and Hernández [157], Eq. (26), is appropriate for large distances, whereas that of Quarton [161]), Eq. (28), gives a better fitting for smaller distances.

7.3. Wind farm wake expressions

For wind turbine clusters Luken [160] proposed a correlation for the equilibrium value of the turbulence intensity reached in a row of turbines, using the experimental results of Builtjes and Vermeulen [162], in which the turbulence decayed like $x^{-1.64}$, x being the distance between machines. Frandsen et al. [194] presented correlations giving values of the average velocity, turbulence intensity, turbulence scale and width of the wake at different positions of each machine in a row as functions of their operating characteristics. These correlations are obtained by making the best fit with numerical results from UPMWAKE, and are validated by comparison with measurements made in Vindeby wind farm. Frandsen and Thøgersen [202], based on the distributed roughness model of Frandsen [261], considered the case of an infinitely large wind farm that perturbs the whole boundary layer, and estimated the value of the added turbulence intensity deep inside the

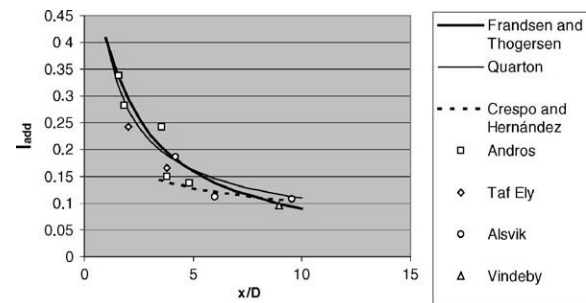


Fig. 44. Maximum, added hub height wake turbulence measured in four different cases, compared with the three correlations: (26), (28), and (29), with adjusted coefficients. Wind velocities in the range 9 m/s < U < 11 m/s. The experimental data were compiled by Ghaie (Personal communication to Frandsen, 1997). Figure taken from [269].

farm to be

$$\Delta I = \frac{0,36}{1 + 0,2\sqrt{x_r x_f}/D/\sqrt{C_T}} \quad (30)$$

where x_r is the separation of rows, and x_f the separation of files. This equation gives a maximum value of $\Delta I = 0.36$ that is equal to the one obtained by Crespo and Hernández [157], for the annular peak of turbulence intensity in the cylindrical shear layer formed in the near wake. This correlation agrees well with the predictions made in [262], as can be seen in Fig. 43.

The effect of atmospheric stability (expressed in terms of the Richardson number) on velocity deficit decay was taken into account in the correlation given by Magnusson and Smedman [177].

All these correlations have been compared with some experimental results and show at least an acceptable degree of agreement, although more work is needed to carry out a full comparison both among these correlations and with experimental results.

8. Concluding remarks

At a time when it is realised that the matter of interest is really complicated, it is worthwhile to review the work that has been done. Hopefully, this overview will provide a point of departure for ‘plunging’ into the subject.

8.1. Near wake

With regards to the near wake experiments, it can be concluded that the wealth of experimental data for helicopters is regrettably not present for wind turbines. In this respect, it is not the quantity that matters, because even when restricting to the uniform, static, non-yawed case, there is a lot of experimental work done on wind turbine near wakes. However, most of these experiments tend to be fragmentarily carried out, meaning they deal only with a limited set of rotor properties. The experiments themselves certainly achieve their own described goal. But most of them seem to be individual and limited efforts. In a larger perspective, by the great diversity in rotor models and wind tunnels, it is extremely difficult to make a comparison between the different experiments and trying to combine them to gain an added value appears to be unfeasible.

The lack of an extensive data set with such basic aerodynamic rotor properties is often felt as a large deficiency, in both the scientific and the engineering environment, for comparison with calculational codes. So, initiatives like the measurement campaign by NREL in the NASA-Ames wind tunnel and the EU-funded “MEXICO” project (with forthcoming measurements in

the DNW wind tunnel) are highly appreciated, but definitely need to have a continuous follow-up.

Near wake computations can be carried out by various numerical techniques, ranging from inviscid lifting line/surface methods to viscous Navier–Stokes based methodologies. Each method has its own advantages and limitations. While e.g. prescribed vortex wake methods are fast to run on a computer but leaves much of the physics to a priori given assumptions, Navier–Stokes based methods offer very detailed insight in the flow behaviour but are very computing costly. There is no doubt, however, that full-blown Navier–Stokes simulations now are reaching a level where they convincingly have matured to become the most important predictive tool for predicting and understanding aerodynamics of modern wind turbines.

8.2. Far wake

With regards to far wake analysis, wind turbine wakes have been extensively studied both experimentally and analytically. Nevertheless, their knowledge is far from being satisfactory. Many of the numerical models proposed show an acceptable degree of agreement with the experiments with which they are compared. However, the assumptions and coefficients that are chosen are such that the agreement with some particular experiments may be good, although the overall validity has not been checked in more general situations. There is a clear need for serious and conscious checks against independent data, as it is made in the project ENDOW, [256,257]. The models which depend on the least simplifying assumptions are better suited in dealing with different configurations and in reproducing wake development in more detail. Some aspects of individual wake modelling, such as near wake representation, influence of atmospheric stability, appropriate turbulence modelling, or convergence problems, are still issues of active research. Some of these aspects are more relevant to the offshore wind farms, many of which are expected to be installed in future. While greater emphasis used to be directed to the estimation of velocity deficits and farm efficiency in terms of energy production, research is nowadays more oriented to other issues, such as estimating magnitudes related to the structural and fatigue behaviour, or fluctuations in the electrical energy produced by machines affected by upstream wakes. For this, it is necessary to know the turbulence characteristics of the flow (turbulence intensity, correlations and spectrum), and wind shear data. An issue of some importance, and in which some progress has been made, is the non-isotropic nature of the turbulence of ambient atmospheric flow, in contrast to the more isotropic turbulence in the wakes. One of the most important difficulties that has not been treated satisfactorily is the choice of appropriate input parameters to define

ambient unperturbed flow, particularly in complicated terrains. Usually, a comparison with wind tunnel experiments is reasonably straightforward, but when field experiments are used for comparison there are many difficulties and effects like meandering, that have not yet been satisfactorily modelled. The results obtained from experimental and modelling studies for terrains of varying roughness and the appearance of internal boundary layers, such as those observed in large wind farms located near the coast or offshore, should be incorporated into the description of ambient flow. The problem is that it is difficult to envisage general solutions, and we will always be solving particular problems that, at most, could only point to general tendencies.

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**BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA**

**IN THE MATTER OF THE
APPLICATION OF DEUEL HARVEST
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY**

* **JON HENSLINS'S RESPONSE TO**
* **STAFF'S FIRST SET OF DATA**
* **REQUESTS TO INTERVENORS**
* **EL18-053**
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Below, please find Staff's First Set of Data Requests to Intervenor. Please submit responses within 10 business days, or promptly contact Staff to discuss an alternative arrangement.

1-1) Provide copies of all data requests submitted to or by you and copies of all responses provided to those data requests. Provide this information to date and on an ongoing basis.

1-2) Refer to SDCL 49-41B-22.

a. Please specify particular aspect/s of the applicant's burden that you intend to personally testify on. None at this time.

b. Please specify particular aspect/s of the applicant's burden of proof that you intend to call a witness to testify on. None at this time.

1-3) Refer to SDCL 49-41B-25. Identify any "terms, conditions, or modifications of the construction, operation, or maintenance" that you would recommend the Commission order. Please provide support and explanation for any recommendations.

a. Specifically, what mitigation efforts would you like to see taken if this Project is constructed.

---Provide 2 mile radius safety zone for all bald eagle nests.

---Provide ADLS

---Provide Property Value Guarantee for nonparticipants in siting area.

---Review Lease and Easement Agreements and Good Neighbor Agreements to assure compliance with State and Federal Laws and Rules.

---List is not all inclusive.

No support or further explanation at this time.

1-4) Please list with specificity the witnesses that you intend to call. Please include name, address, phone number, credentials and area of expertise. None at this time.

1-5) Do you intend to take depositions? If so, of whom? Not at this time.

Dated this 20th day of February 2019.

/S/ Jon Henslin
Jon Henslin

**BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA**

**IN THE MATTER OF THE
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY**

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**RESPONSE TO APPLICANT'S
FIRST SET OF DATA
REQUESTS TO JON HENSLIN**

EL 18-053

Below, please find Deuel Harvest Wind Energy LLC's ("Applicant") First Set of Data Requests to Jon Henslin. Please submit responses within 10 business days or promptly contact the undersigned to discuss an alternative arrangement.

1-1) Provide copies of all data requests submitted by PUC staff to you in this proceeding and copies of all responses to those data requests. Provide this information to date and on an ongoing basis.

1-2) Identify the address of your permanent residence (where you reside).

1020 Lake Alice Drive
Clear Lake, South Dakota 57226

1-3) Identify all property you own within the vicinity of the Deuel Harvest North Wind Farm ("Project") and the location (by section, township, and range) of such property. Are there any habitable buildings on the property you own?

Altamont Township, Lake Alice Shores, 7-116-48, Lot 10
Yes, our home is on this lot.

1-4) If you have a residence in the vicinity of the Project, identify whether you live at the residence throughout the entire year and, if not, how many months of the year you reside at the residence.

Entire year; however, have occasionally taken a month vacation in the winter.

1-5) Identify how you use your land, including, but not limited to, whether you use your land for agricultural purposes.

As our primary residence, and since it is on the lake, recreation (fishing etc.).

1-6) Identify any sensitive or unique features of your property that you assert would be impacted by the Project.

I am concerned that the view (day and night), sound, property value, and flashing red lights could negatively impact my property.

1-7) Describe your concerns regarding the Project.

Effects on property values
Constant Flashing Lights
Bald eagle nest on north end of Lake Alice.
Contracts
Health effects

1-8) Describe what mitigation measures would address the concerns you identified in response to Request 1-7 and whether any of the mitigation measures identified by the Applicant in its Application could address any of your concerns.

Provide property value guarantees for nonparticipants in the siting area.

Provide ADLS – I believe the applicant plans to use ADLS; but would like assurance.

Provide two-mile radius safety zone for all bald eagle nests, including the nest identified at the PUC public hearing held in Clear Lake on this project.

Have the PUC or the State Attorney General Office review the lease and easement agreements to make sure the documents follow state and federal laws and rules.

The health effects mitigation measures would be tied to setbacks.

1-9) Identify any documents, information, education, training, or professional experience you have relied upon to form your opinions concerning the Project. Where you have relied upon documents or other tangible materials, please provide such documents and/or materials.

Graduated from SDSU with a BS degree in Engineering in 1971.
Licensed Professional Engineer (PE) in Minnesota.
39 Years of work experience with Minnesota Department of Transportation.
Retired in 2011.

Some materials I have relied upon:
Deuel County Zoning Ordinance
South Dakota Energy Siting Rules (Chapter 20:10:20)
South Dakota Codified Law Title 49
Invenergy (Special Exception Permit Application dated December 2017)
PUC Docket EL 053
List is not all inclusive.

1-10) Identify any witnesses, including expert witnesses, you plan to have testify on your behalf. For each witness (including expert witnesses), please provide a resume or statement of qualifications of the witness(es), identify the subject matter regarding which the witness will testify, and identify and provide any exhibits the witness will refer to or introduce.

None, at this time.

1-11) Are you asserting that the Project will negatively impact your property value? If so, provide copies of any appraisals or other valuations that have been conducted for such property within the last ten years.

I am concerned that this project will negatively impact my property. I do have a copy of an appraisal on my home. It was made when I applied for a mortgage. We had the home built for us and when the appraisal was made the construction had just started. The appraisal was based primarily on the house plans. However, major changes were made that greatly increased the square footage of finished living space. As a result, the appraisal is by no means accurate. Currently my wife and I are on vacation until the beginning of April. I did not bring a copy of the appraisal along. I would gladly provide you with a copy of the appraisal when we return. The home is currently for sale.

1-12) Identify any communications, written or otherwise, you have had with units, officials, and/or representatives of local, state, and/or federal governments or agencies concerning the Project.

a) For any written communications, provide a copy of the communication;

December 6, 2017 email to Senator Rounds

I know congress is working on a tax bill that is generating a lot of press. I am very much concerned about our national debt; let us not leave a legacy of debt to our children and grandchildren.

One item that I feel it is time to do away with is the Production Tax Credit (PTC) for Industrial Wind Turbines. Over the last year there has been a lot of debate about wind turbines in Deuel County. It is very obvious that (despite what the developers say) these wind farms are not feasible without the PTC. The bottom line is that the tax payers are paying for a large amount of the initial cost in PTC and continue to subsidize the Wind Farms thru increases in our electric bills. I obtain electricity from two cooperatives; both identify the cost of solar and wind energy as a reason for rate increases. Yet the wind developers claim that wind will provide cost savings to the consumers.

Wind developers have repeatedly informed me that Wind Turbines do not affect property values. A 500 ft. wind turbine installed 1000 feet of your home does not affect property value? If there is no effect on property values, why have all three companies currently planning wind farms in Deuel County refused to provide any property value guaranties?

Representatives of one of the wind farm developers visited with my wife and I. They wanted us to sign a lease agreement. I asked them why, since we own a home on a lake and our lot is less than an acre in size. They told us it was to make sure we did not construct a tall structure on our property. That did not make much sense to me since our zoning already has height restrictions. We did not sign but they left a copy of an agreement with us. I later read the agreement over and what I found was rather disturbing. It would be nice to discuss the contents of the agreement with you and/or your staff. Have you had the opportunity to read one of these agreements? If not I would gladly provide you with a copy of the one given to me.

In closing I encourage you to consider doing away with the PTC or at the very least not extending it. I would appreciate the opportunity to discuss the lease agreement with you or your staff.

Sincerely

Jon Henslin

March 23, email to Josh Haeder

Josh,

I truly appreciate your call this morning. Attached is the first half of the lease agreement being used for the Deuel County wind farm. I will be sending the second half in another email due to the size of the document. I will try to obtain a copy of the Good Neighbor Agreement. I left you a phone message asking if next Monday March 26 at 1:00 PM would work for you to meet with us at our home.

Looking forward to that meeting.
Jon Henslin

Quoting "Haeder, Joshua (Rounds)" <josh_haeder@rounds.senate.gov>:

Thanks for speaking with me, shoot over copy of contract to this email and I will review.

Thanks,

Josh Haeder

Northeast Director | Sen. Mike Rounds (R-SD)

March 24, 2018 email to Josh Haeder

Hi Josh,

We did send you a copy of the lease and easement agreement however it bounced back to us because the size was too large to be accepted by the senate server. I will break it down to fewer pages per attachment so hopefully it will go through this time.

We would like to meet with you on Monday at 1:00 PM if that doesn't work anytime on Monday would work or anytime Wednesday until 4:00 PM or anytime Thursday until 4:00 PM. We added these extra times due to the weather and the message bouncing back. Hope one of those works for you.

Jon

April 2, 2018, meeting with Josh Haeder

April 5, 2018, email to Josh Haeder

Hello Josh,

Josh, thank you for taking the time to meet with Nancy and I on Monday. I hope we didn't keep you too long. We would not want to interfere with your daughters' elephant rides!

You had requested some layouts of the Deuel Harvest North and south Wind Farms and they are attached. We will be sending an additional map that shows both project's footprints. We are sending it separately due to the size of the attachments.

The maps show the project footprints, turbine locations and residences (participating and non-participating). At the Special Excepting Public Hearing the Developer provided the County with three maps showing various possible turbine locations for each project North and South (the zoning regulations call for a map - singular). The Developer requested approval with the stipulation that they could change the number and location of the turbines in the final layout submitted for a building permit, as long as they met the Counties zoning regulations and stayed within the project footprint. The Special Exception was granted. We can discuss this further at our next meeting.

Could we schedule another meeting at our home on April 17th, 18th, 19th or 20th? We do have some other residents that would like to share their concerns. If possible plan for a two hour visit. We can furnish coffee and a veggie/fruit plate.

Again thank you for listening to our concerns.

Jon and Nancy Henslin

April 23, 2018, second meeting with Josh Haeder

April 5, 2018 email to Josh Haeder

Dear Josh Haeder,

Josh, I don't know how to put into words the enormous amount of appreciation that Nancy and I have for you taking the time to meet with us. I know the whole group that was here Monday shares that sentiment. It was refreshing to have someone sincerely listen to our concerns.

I know you heard from us that we are not against wind energy. If you had the time to listen to the entire video of the January 22, 2018 Public Hearing, regarding Invenergy's application for a Special Exception to construct two Wind Energy Systems (WES) in Deuel County; that fact would be evident. However, we are concerned about the effects of WES on health, property rights, and property values. We are also concerned about the approval process, funding, and overall plan (including cost vs benefit).

Wind Lease and Easement Agreement

Josh at our first meeting we reviewed a Wind Lease and Easement Agreement used by Invenergy. Attached you will find another Wind Lease and Easement Agreement that is being used in South Dakota by Crown Ridge Wind Energy Center LLC., an affiliate of NextEra Energy Resources, LLC. I did quickly read thru the agreement and found many items that were similar to those we addressed in the Invenergy Agreement. You can have your legal staff review it. I did wonder about the last sentence in 3.5 Exercise of Option, you may want to look at that.

Lighting

At the Monday meeting I gave you a handout on Lighting. I would like to explain that handout better. Number the sheets from 1 to 6 and the explanation is as follows.

Page 1, is a fact sheet I prepared regarding lighting for the WES projects that were approved at the January 22, 2018 Board of Adjustment Meeting.

Page 2, is the presentation that Nancy Henslin gave at the January 22, 2018 meeting.

Page 3, on this page the highlighted area is Section 504.5.e (Deuel Co. Zoning), which refers to exterior lighting. Also refer to item 5 on this page where it states "satisfactory provision and arrangement has been made concerning the following" (which includes exterior lighting and turbine lights are exterior lights).

Page 4, on this page the highlighted area is Section 1215.03.4 (Deuel Co. Zoning), which addresses FAA requirements.

Page 5, this page is copied from Invenergy's Special Exception permit application. The highlighted area refers to Section 504.5.e. The only exterior lighting addressed is lighting for their O&M Building.

Page 6, this page is copied from the Board of Adjustments' Findings of Fact for Invenergy's Special Exception. In its Findings of Fact the Board of Adjustment fails to even identify exterior lighting.

Comments: The constant blinking red turbine lights, cause light pollution and negatively impact the public's property value and quality of life. The technology to reduce this negative effect is readily available. The question is who is going to require it; County, State, or Federal? Our experience in Deuel County has been that it is not working at the County level even though the County has the authority and responsibility to address the lighting issue. The Developer (Invenergy) has not been willing to provide the technology and at the public hearing for the Special Exception provided false information regarding the Aircraft Detection Lighting System. It appears that the State or Federal government would be the most effective level for implementation. In Deuel County alone the number of wind turbines could increase from zero in 2010 to over 500+ in 2020 to over 1000+ in 2030. I for one, at night want to look at the heavens and see stars, planets, constellations and the moon on a black background.

Property Value

You were also given a handout on property value. As with lighting I would like to explain it better. Number the sheets from 1 to 9 and the explanation is as follows.

Page 1&2, these pages are taken from Deuel County's Zoning Ordinances and cover Purpose,

Special Exceptions and Power and Jurisdiction Relating to Special Exceptions.

Page 3&4, the top of page 3 discusses the purpose and intent of the zoning regulations. The important part here is: "The regulations are intended to preserve and protect existing property uses and values against adverse or unharmonious uses...". The remaining portion of page three and page four relate to effects of a Special Exception on adjoining properties and properties generally in the district. It documents the input we provided the Board of Adjustments at the January 22, 2018 Public Hearing. It also documents the response given by Invenergy.

Page 5, the area highlighted on this page refers to that portion of the county zoning that addresses the effects of the special exception (WES) on adjoining properties and properties generally in the district. The effects mentioned were economic, noise, glare, odor, or other effects. The Board of Adjustment is required to make written findings certifying that satisfactory provision and arrangement has been made concerning these effects. This was not done.

Page 6, the area highlighted was taken from Invenergy's special exception permit application. This section was to address section 504.5.b. It covered the off-street parking portion but completely eliminated the portion related to the effect of the WES on adjacent properties etc..

Page 7, the area highlighted is taken from the Board of Adjustment's Findings of Fact regarding 504.5.b.

Page 8 is an interesting letter put together by Brenda Taylor (Deuel County citizen). In it she documents actual cases where home owners in Deuel/Brookings Counties have had problems selling properties after wind turbines were constructed. The information from local relators is also interesting.

Page 10 is a copy of a letter I sent to the Clear Lake paper regarding property value guarantee. Comments: Do wind turbines effect property value? I am convinced the answer is yes. I have always heard that in real estate the rule is location, location, location. Realtors I have spoken with tell me that wind turbines have a negative impact on property values. Of course if one is purchasing just land with turbines on it and you obtain revenue off them that could be different. Most of the articles I have read state, there is no negative effect due to the presence of wind turbines, have been based upon Spatial Hedonic Analysis. It is interesting that Ben Hoen, the author of many of those reports, in an interview in 2010 stated "I think one of the things that often happens is that (wind) developers put our report forward and say look property values aren't affected, and that's not what we would say specifically. On the other hand, they have little ground to stand on if they say we won't guarantee that." It also appears to me in the Spatial Hedonic Analysis there are a lot of characteristics included for the homes in the study area, which is good. However, it appeared to me that turbine characteristics were not well defined. For example a one hundred foot tall turbine would not have the same effect as a 600 foot turbine at the same distance from a home. Also only the closest turbine distance was considered in the analysis. Obviously a home with one turbine within a mile will be less impacted than a home with 8 turbines in a mile. The amount of negative impact on a home's value increases rapidly as the distance to the turbine decreases. Wind Turbines do negatively affect property values.

Invenergy has assured us that this project (discussed earlier) will not affect property values, which is not true. Our Board of Adjustment has approved the special exception for this project without providing written findings certifying that satisfactory provisions and arrangements have been made concerning these effects. Who will protect the property rights and values in South Dakota Counties? For us the county is not doing the job. Who should? It appears to me that it

would be a State or Federal issue. Another option would be the Counties/State providing training for County Zoning Officers/Boards/States Attorneys. Property values/rights are an important issue, with the large number of current and potential projects, timing is critical. Maybe a moratorium is a logical course of action.

Again Josh thank you for making time in your work schedule to visit our home and listen to all of our concerns.

Sincerely

Jon and Nancy Henslin

August 12 2018 text message to Josh Haeder

Good morning Josh, did you prepare any findings or get any legal opinions done on wind leases?
Jon and Nancy Henslin How is you campaign going?

October 16, 2018 presentation to the Deuel county Commissioners.

The two Deuel Harvest and the portion of Crowned Ridge in Deuel County have a projected cost of about 900 million dollars. The projects have a combined foot print of about 85 thousand acres which is over 20 percent of the land in Deuel County. The impact of these projects (positive and negative) will affect 100 percent of the county.

I am here today as a citizen of Deuel County to express my concerns about the Public Hearings that were held regarding the Special Exception Applications for these projects.

How effective have the hearing been?

Invenergy, NextEra and wind lease holders may feel the hearings were excellent.

Many who had concerns about the projects are probably disappointed.

Most Deuel County residents did not attend the hearing so would not have any comments on its effectiveness. I remember prior to the vote on the Invenergy application one of the board members stated regarding the application document: "I think you all have access to (pause) I'm not 100% sure, but if you want to see it(application) it is up at the zoning office. It's been published for a long time". I doubt that 1% of the voting members of Deuel County have read what was in the application. With all of Deuel County being affected by these two projects, more effort should have been put into educating Deuel County residents.

At the Public Hearing for Deuel Harvest, the number of speakers was limited to about 25, with each speaker allowed three-minutes. Which calculates to 90 seconds per project. At the Public Hearing for Crowned Ridge no limits were placed upon the number of speakers, however, a three-minute time limit was again used. Since there was a time limit imposed, many of the speakers were not able to communicate their whole concern, which is unfortunate. Some presenters brought along printed copies of their presentations and supporting data so that it could be reviewed by the Board, if the speaker were unable to complete their talk in the three minutes. In the case of Deuel Harvest Wind, providing printed copies was a waste of time for the board

voted on the Special Exception that evening. They had no time to consider the printed information provided.

One of the concerns that I had was flashing red lights. At the Public Hearing for Deuel Harvest, it was suggested that an Aircraft Detection Lighting System be used. When the Board asked Invenergy about the use of that system, Invenergy said that Aircraft Detection Lighting System was unproven technology, which is untrue.

When the Public Hearing was held for Crowned, the Board asked about the use of an Aircraft Detection Lighting System. NextEra indicated an Aircraft Detection Lighting System would require a two-step approach and that it would be a “departure from the intent” of a lighting system. Wrong on both accounts. The intent of the lighting system is to warn aircraft not provide constant flashing lights. The Aircraft Detection Lighting System provides the required aircraft warning. An Aircraft Detection Lighting System and a constant flashing lights system have the same approval process.

Any Wind Energy System developed in Deuel County or expanded in Deuel County should require an Aircraft Detection Lighting System. Since Invenergy provided incorrect information their Special Exception should be amended to include an Aircraft Detection Lighting System.

I am also concerned about property value impacts. Special Exception Application Documents prepared by Invenergy and NextEra do not address property value impacts on adjacent properties. The Board of Adjustments is specifically required to consider the property value impacts on adjacent properties.

Commissioner Steve Rhody allowed me to question Invenergy about property value impacts not being included in their Special Exception Permit application. Invenergy spoke but did not provide an answer to the question.

NextEra was asked about the effects of their project on property values – specifically regarding non-participants. Their response indicated there are no long-term negative impacts on home values. NextEra’s representative spoke of an extensive study consisting of 50,000 homes in 9 states and 27 counties that found no net negative or positive effects.

The extensive study referred to was done by the Lawrence Berkeley National Laboratory (LBNL). It is interesting that Ben Hoen, the primary author of the extensive report has said:

“I think one of the things that often happens is that (wind) developers put our report forward and say look property values are not affected, and that’s not what we would say specifically. On the other hand, they have little ground to stand on if they say we won’t guarantee that.”

That statement should ring a bell with you. During the Hearing held to update the Wind Energy System ordinances Gary Dejong told the Wind Energy System developers to: “Put their money where their mouth is” in regard to property value guarantees.

I have copies of a few papers that address problems related to the extensive study identified by Next Era. One of the authors Albert Wilson states “the Report should not be given serious consideration for any policy purposes. The underlying analytical methods cannot be shown to be

reliable or accurate”. Another article by Michael McCann states “Regardless of terminology or focus, the fact is that the raw data shows a post construction negative impact of 28% for homes less than 1-mile from turbines vs. homes in the 3-10-mile range”

The visual impact of wind turbines has been researched. It is interesting that the number of turbines visible and the distance to the turbines both affect property value. One research study (Yasin Sunak and Reinhard Madlener) identifies over 10% reduction in property value if eight or more turbines were visible.

The PUC hired David Lawrence, a South Dakota State-Certified General Appraiser. He was hired to determine if the studies and testimony of the applicant adequately reflect the potential impact to the value of properties in the vicinity of the proposed Crocker Wind Project. His answer was:

“It is my opinion that the studies and testimony do not provide adequate market evidence that can be applied to the subject area of the Crocker Wind Project.” Note these studies included the LBNL studies referenced by NextEra.

About a month later, David Lawrence was again hired by the PUC to review Dakota Range I and II. He was again asked the same question related to that project. His answer was:

“It is my opinion the studies and testimony presented by Dakota Range provide a good starting point; however, the studies presented have limitations that need to be considered for their applicability to South Dakota.” Note these studies included the LBNL studies referenced by NextEra.

David Lawrence believes; a comprehensive study from the market area of South Dakota will provide the evidence that is required to determine the potential impacts of a wind energy project on property values. The methodology that is applicable in this type of study is referred to as the case-by-case sales comparison approach which provides a more reliable alternative to the hedonic analysis.

I believe the comprehensive study identified by David Lawrence needs to be done immediately. Such a study would take about 6 months. The study would provide a reliable tool in South Dakota to assess impacts on property values. Any Special Exceptions approved prior to the completion of such a study needs to include a property value guarantee.

Getting back to the Public Hearings. The items I brought before the Board of Adjustment at the Deuel Harvest Public Meeting were not adequately addressed. Satisfactory provisions and arrangement should have been made for these issues. Others who tried to express their concerns in the 3 minutes provided, felt the same way. It appeared the public hearing for Deuel Harvest had been scripted ahead of time (possibly by First District). Our voices were heard, but very little was listened to.

Regarding the Crowned Ridge Hearing, 30+ speakers addressed the Board of Adjustments. Were any asked follow up questions? I hope that is not an indication that they were only heard

but not listened to. It is encouraging that the Board did not immediately vote on the Special Exception. Not voting will allow them time to consider the public input provided.

In closing:

The Special Exception process for large Wind Energy Systems can be very difficult. To move forward with these complicated projects, every “I” must be dotted and every “T” crossed. Doing it right will take time. The application needs to be gone thru line by line and if deficiencies are found, address them and if concerns are raised, solutions should be explored. We must remember that our requirements listed in the ordinances are minimum requirements and if needed, more strict measures may be taken. The Board must religiously adhere to the responsibilities given to them in the zoning regulations including those associated with Special Exceptions. The public should be well informed regarding projects of this magnitude. One or more public information meetings may be necessary. Public Hearings should be conducted in such a manner that the public feels their input is listened to and considered by the Board members. Enough time must be provided for the public to present their input.

January 22, 2018, presentations for the special exception public meeting.

Effects on Adjoining Properties

Deuel County Zoning states in section 504 the following:

Part B in this section refers to two separate items. One is off street parking and loading areas which Invenergy’s application addresses. However the second part of this ordinance refers to **the economic, noise, glare, odor or other effects of the special exception on adjoining properties and properties generally in the district.**

The economic, noise, glare, odor or other effects are those caused by the special exception which is the Wind Energy System (WES) not the off-street parking and loading areas. These items need to be addressed, especially the economic effects of the turbines on adjacent residences and businesses.

7.5 Permit Expiration

Deuel County Ordinance addresses the expiration of a Wind Energy System Special Exception Permit. It states: “the permit shall become void if no substantial construction has been completed within three (3) years of issuance.”

The Deuel Harvest Wind has requested that substantial construction be defined as ‘pouring a single foundation within the project footprint’. This definition is the definition used in SD Codified Law to define the “development of potential to produce energy”.

The two definitions are not interchangeable. For a large Wind Energy System (WES) the pouring of a single foundation does not seem to constitute substantial construction. Leaving the

wording as it currently reads in the zoning, retains control in the county and requires the permittee to show substantial progress. The county can always extend the permit if necessary.

In addition if Invenergy hold to the project schedule provided, construction will be completed in less than 2 years for the North Project and less than 3 years for the South Project.

Decommissioning Plan

Deuel County Zoning states in part: the decommissioning plan shall include the permittee post a bond or other adequate security sufficient to pay the entire cost of the decommissioning process.

Deuel Harvest states in their application regarding the decommissioning process the following. To avoid duplication and potential conflicts in obligations Deuel Harvest requests that the county defer to and accept the SDPUC's final decision on financial assurance.

However the SD Energy Facility Siting Rules states the following regarding decommissioning of Wind Energy Facilities (20:10:22:33:01)

Decommissioning of wind energy facilities -- Funding for removal of facilities. The applicant shall provide a plan regarding the action to be taken upon the decommissioning and removal of the wind energy facilities. Estimates of monetary costs and the site condition after decommissioning shall be included in the plan. The commission **may require** a bond, guarantee, insurance, or other requirement to provide funding for the decommissioning and removal of a wind energy facility. The commission shall consider the size of the facility, the location of the facility, and the financial condition of the applicant when determining **whether to require some type of funding**. The same criteria shall be used **to determine the amount of any required funding.**"

As stated earlier Invenergy has requested in order to avoid duplication and potential conflicts in obligations, Deuel Harvest requests that the County defer to and accept the SDPUC's final decision on financial assurance. However by so doing the County may not receive the adequate security that our ordinance requires. The ordinance states: The decommissioning plan shall include the requirements that Permittee post a bond or other adequate security sufficient **to pay the entire cost** of the decommission process.

Invenergy's request does not assure adequate security nor full cost of the decommission process; therefore it would not be prudent to grant this request.

Lighting

The Deuel Harvest Special Exception Permit Application contains information on lighting.

I would like to submit the following regarding the lighting of turbines.

Last year North Dakota signed into law a bill which requires "Light-Mitigating Technology Systems" on Wind Energy Systems (WES) capable of producing more than 500 kW of electricity. The system first proposed was an Aircraft Detection Lighting System (ADLS). In December of 2015, FAA introduced standards for ADLS. The first FAA approved commercial

operation of an ADLS was installed in Wyoming NY. The Wyoming NY installation was very effective. An article about this installation stated “Since we turned the system on in Wyoming, we regularly see nights where the lights are off 99% of the time.”

What will Deuel County look like in 5-10 years? If Wind Energy Systems (WES) continue to expand in the county, and additional phases add more and more turbines within the footprints of existing Wind Energy Systems (WES), we will no longer have the prairie view that was so familiar to indigenous peoples and our forefathers. The landscape will be a metal forest of turbines. However, at night, if the Aircraft Detection Lighting Systems (ADLS) is installed, we may be able to enjoy the same view of the stars that those who were here before us marveled at years ago.

I believe that if a public meeting had been held on these two projects and our citizens (participating and non-participating) had been allowed to freely express their views on this subject, the vast majority would have requested the red lights remain dark and only flash when an aircraft is detected.

We encourage the Board of Adjustment to require that all turbines in Deuel County have Aircraft Detection Lighting System (ADLS) technology. This technology should be part of the initial construction not delayed to be incorporated at a later date.

And

b) For any unwritten communications, provide the date of the communication, the persons involved, and the subject matter of the communication.

January 2019, met with Adam Behnke, Conservation Officer (SD Game Fish and Parks), subject matter bald eagle nest.

September 18, 2018, voice message from Jennifer Hieb regarding response from Senator Rounds regarding PTC.

January 2019, phone call with Josh Haeder regarding legal opinions on wind leases.

1-13) With respect to your statements at the January 24, 2019, public input hearing, state all facts that support the statements you made and produce copies of all documents that support statements you made.

All statements should be supported in the information provided to the PUC. One exception is the article related to Suicide. That article can be found at:

<https://docs.wind-watch.org/Zou-suicide-2017-Oct.pdf>

Dated this 26th day of February 2019.

By /s/ Jon Henslin

Jon Henslin

1020 Lake Alice Drive

Clear Lake, South Dakota

jnhenslin@itcmilbank.com

**BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA**

**IN THE MATTER OF THE
APPLICATION OF DEUEL HARVEST
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY**

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**STAFF'S FIRST SET OF DATA
REQUESTS TO INTERVENORS**

EL18-053

Below, please find Staff's FirstSet of Data Requests to Intervenor. Please submit responses within 10 business days, or promptly contact Staff to discuss an alternative arrangement.

1-1) Provide copies of all data requests submitted to or by you and copies of all responses provided to those data requests. Provide this information to date and on an ongoing basis.

1-2) Refer to SDCL 49-41B-22.

a. Please specify particular aspect/s of the applicant's burden that you intend to personally testify on.

Turbine placement that will threaten the social and economic condition of inhabitants and expected inhabitants in the siting area.

Turbine placement near environmentally sensitive areas.

b. Please specify particular aspect/s of the applicant's burden of proof that you intend to call a witness to testify on.

None at this time.

1-3) Refer to SDCL 49-41B-25. Identify any "terms, conditions, or modifications of the construction, operation, or maintenance" that you would recommend the Commission order. Please provide support and explanation for any recommendations.

a. Specifically, what mitigation efforts would you like to see taken if this Project is constructed.

I recommend the Commission to order the applicant to adhere to the 2-mile buffer given to the eagle nests outside of the project area to be the same for the eagle nest that has been monitored the past two years, north of Lake Alice a half mile.

I recommend the Commission to review the placement of turbines that are in close proximity of bird movement corridors and concentrated bird and/or bat use areas. Set back of 1 mile to these areas.

I recommend the Commission to study the impact that turbine placement will have on future development of non-participating landowners. Currently, if the project was completed to today, future development on my property at the old homestead would

be within the setback established in the Deuel County Ordinance B2004-01 Section 1215.03 Section 2a. Distance from existing Non-Participating residence and businesses shall be not less than four times the height of the wind turbine. Distance from existing Participating residences, business and public buildings shall be not less than fifteen hundred feet. Non-Participating property owners shall have the right to waive the respective setback requirements. I want the setback from the building site to be what the county ordinance reads. My property is located Glenwood Township T-116-N, R 48 Sec. 34

I recommend the Commission to reevaluate turbine placements next to ecological sensitive areas and give them a 2 mile setback.

I recommend the commission to review turbine placements next to non participants and give them a setback of 1 mile from their property line to protect their rights.

No further support or explanation at this time.

- 1-4) Please list with specificity the witnesses that you intend to call. Please include name, address, phone number, credentials and area of expertise.

None at this time

- 1-5) Do you intend to take depositions? If so, of whom?

None at this time

EL18-053 - In the Matter of the Application of Deuel Harvest Wind Energy LLC for a Permit of a Wind Energy Facility and a 345-kV Transmission Line in Deuel County

Applicant First Set of DR

Heath Stone

1-2) 803 Lac Qui Parle St. Gary SD 57237

1-3) Personal Property- Glenwood Township T-116-N, R 48 Sec. 34
Stones Conservation Partnership LLP-Glenwood Township T-116-N, R48 Sec. 34,35
No habitable buildings

1-4) No residence

1-5) South Dakota Pheasant Hunts is a licensed preserve that operates its business on the property listed above. This is the main source of income derived from the property. My family enjoys the property for its peace and quietness and plentiful wildlife that inhabit the area. Outdoor recreation, education and preservation of habitat are the main focus of the property. Every fall hunters come and enjoy pheasant hunting on our property. Food plots are planted in the spring and haying some portions of the property is done late summer.

1-6) I have an abandoned building site located near Turbine 103. Future plans are to build a home at the site. There are several deer stands located on the property listed above. The property hosts a variety of wildlife and crucial habitat for grassland bird species that need big blocks of grass to thrive. The property has a diverse community of native fauna that provides habitat for all wildlife and insects.

1-7) As mentioned above, there is an old building site on our property we want to build a house on in the future. Turbine 103 would be within the set back distance of non-participating residences in the Deuel County ordinance. Turbines 103, 109, 110, 111 are in close proximity to the property and will cause uncertainty to our pheasant hunting operation and put our clients at risk if a turbine malfunctions. The turbines close to the property will have a negative impact on the pheasant population since pheasants avoid the areas near the turbines.

Throughout the project several turbines are located near permanent wetlands that are staging areas for waterfowl in the spring and fall migrations and vital for local waterfowl that use these waters to rear their broods. Turbine 6,13, 14, 63,64, 85, 86, 95, 96, 101, 102, 109-115, 118, 119, 120, 121 all pose a direct threat to waterfowl coming and going from these bodies of waters. Waterfowl are sensitive to tall structures next to wetlands and will cause them to avoid them all together.

Turbines throughout the project are located too close to ecological sensitive areas.

1-8) Turbines near non-participating property lines should have a setback of 1 mile. Turbine 103 is restricting future development on my property and turbines 109, 110, and 111 pose a direct threat to our pheasant operation. Turbines 6, 13, 14, 63, 64, 85, 86, 95, 96, 101, 102, 109-115, 118, 119, 120, 121 shall have a setback of 1 mile due to their close proximity to these wetlands that are vital for waterfowl to utilize these bodies of water for brood rearing, roosting and staging.

1-9) I have a B.S. in Wildlife and Fisheries Sciences. I am a conservationist. I have acquired my professional expertise by reading and studying papers and documents to better our habitat, wildlife populations and pheasant operation on our property.

1-10) None at this time.

1-11) None at this time

1-12) Gary Jaeger (County Commissioner)-unwritten, Present-Gary and I, discussion took place about the wind farms that were moving into the area. I voiced my concerns for wildlife and setbacks. Do not remember the date.

Lynn Pederson (County Commissioner)-unwritten, Present-Lynn and I, discussion took place about the wind farms that were moving in to the area. I voiced my concerns for wildlife and setbacks. Do not remember the date.

1-13) A) Personal Property- Glenwood Township T-116-N, R 48 Sec. 34

B) Stones Conservation Partnership LLP-Glenwood Township T-116-N, R48 Sec. 34,35

C) As stated above

EL18-053 In the matter of Application of Deuel Harvest Wind Energy LLC for a permit of a Wind Energy Facility andn a 345-kv Transmission Line in Deuel County

Applicant First Set of Data Requests

Will Stone

1-2) 18203 486th Ave. Gary, SD 57237

1-3) STONES ADD IN SW ¼ N660' W990' NW ¼ SE1/4 STR 35-116-48; SE ¼ LESS BLK 2 HUNT SUB STR 34-116-48; NE ¼ LESS BLK 1 HUNT SUB STR 34-115-48 No buildings on property.

1-5) Land is used as pheasant hunting licensed preserve, where hunters come from every state to enjoy hunting pheasants that we provide. We have spent a life time grooming this land for the pheasant hunting. Some haying and grazing take place.

1-6) We have hunters on our property any time from September 1 to March 31 for the purpose of hunting pheasants. Hunters are out on the property during all weather conditions which may include times there would be ice build up on the wind tower blades that could be thrown on our property putting them in danger. Hunters also comment on how quiet and serene it is, noise from wind towers would compromise that. Many species of native birds nest on property as well as migratory birds, including eagles and hawks and monarch butterflies. Migratory birds use our wetlands as resting areas during spring and fall migrations. Deer also inhabit our acres.

1-7) I am concerned it will effect nesting habits and most wildlife will migrate out of area. I am concerned of unconstitutionally imposing a safety zone on our property and on public right of ways and noise the wind towers create and the economic effects the turbines could have on our hunting business. If our veteran hunters quit coming because of the noise and loss of open views we will lose primary source of income for the property.

1-8) The elimination turbines 109, 110, 111 . Relocating turbines 103 and 112 2000' from our business acres. Relocating turbines 51,52,64,72,A73,A74,A75,82,84,98,1122 and 123 so they do not impose a safety zone in public right of ways.

1-9) Have studied volumes documents and testimony on wind watch websites and online recording of actual zoning boards and county and city commissions.

1-10) none at this time.

1-11) Loss hunters would impact value of the land to us. It will negatively impact our value by destroying our view of the Coteau hills and our sunrises and sunsets and moon at nights. There is no way it will not affect value.

1-12) I have had communications with all zoning board member and county commissioners but did not document contacts with them. Written comments are a matter of public record in commission meeting minutes.

1-13) Commercial pheasant hunting season is from September 1 to March 31. Hunters also use land for dog training which can take place year round on property. Property is identified in 1-3 above.

1-14) No

1-15) a)

The mention of one of four preserves in my testimony before PUC was just to establish that we have been in business for 35 years as a preserve but have been serving hunters for 63 years.

b) Turbines 103, 109, and 111 unconstitutionally put a safety zone on hunting acres on our property.

c) Turbines 103, 109, and 111 will unconstitutionally impose about a 1000' safety zone on the NW corner and North border line of our preserve acres.

d) see attachment

e) see attachment

f) According to Vesta and Nordex manuals safety zone setbacks these turbines are imposing safety zones on right of ways where school buses travel, people drive, jog and ride bike

g) I can't prove income will decrease, wind company can't prove it won't, but if it does decrease who compensates us. Wind company would not put a clause in contract offered to us, to guarantee compensation of difference if preserve's gross income dropped below current level.

If this application is for a new private shooting preserve permit, you are also required to submit a plan of operation and outline the preserve boundaries on the enclosed plat map. Please include a FSA (SCS) type aerial photo showing perimeters of the proposed shooting preserve. For preserve renewals with acre or boundary changes, please outline the preserve on the enclosed plat map.

The following plat map represents an area of 16 sections. Each of the larger squares (thick border) represents one section of land (640 acres); the smallest squares represent 40 acres. Please outline the boundaries of your shooting preserve area and shade in that portion. Label the section(s), making sure that your sketch conforms to the legal description of the area you are applying for.

NAME OF APPLICANT

SOUTH DAKOTA PHEASANT HUNTS
WILLIAM STONE

40A.	

Each small box = 40 A.

These 4 boxes = 160 A.

DEUEL CO.

T-14N R-47-48W

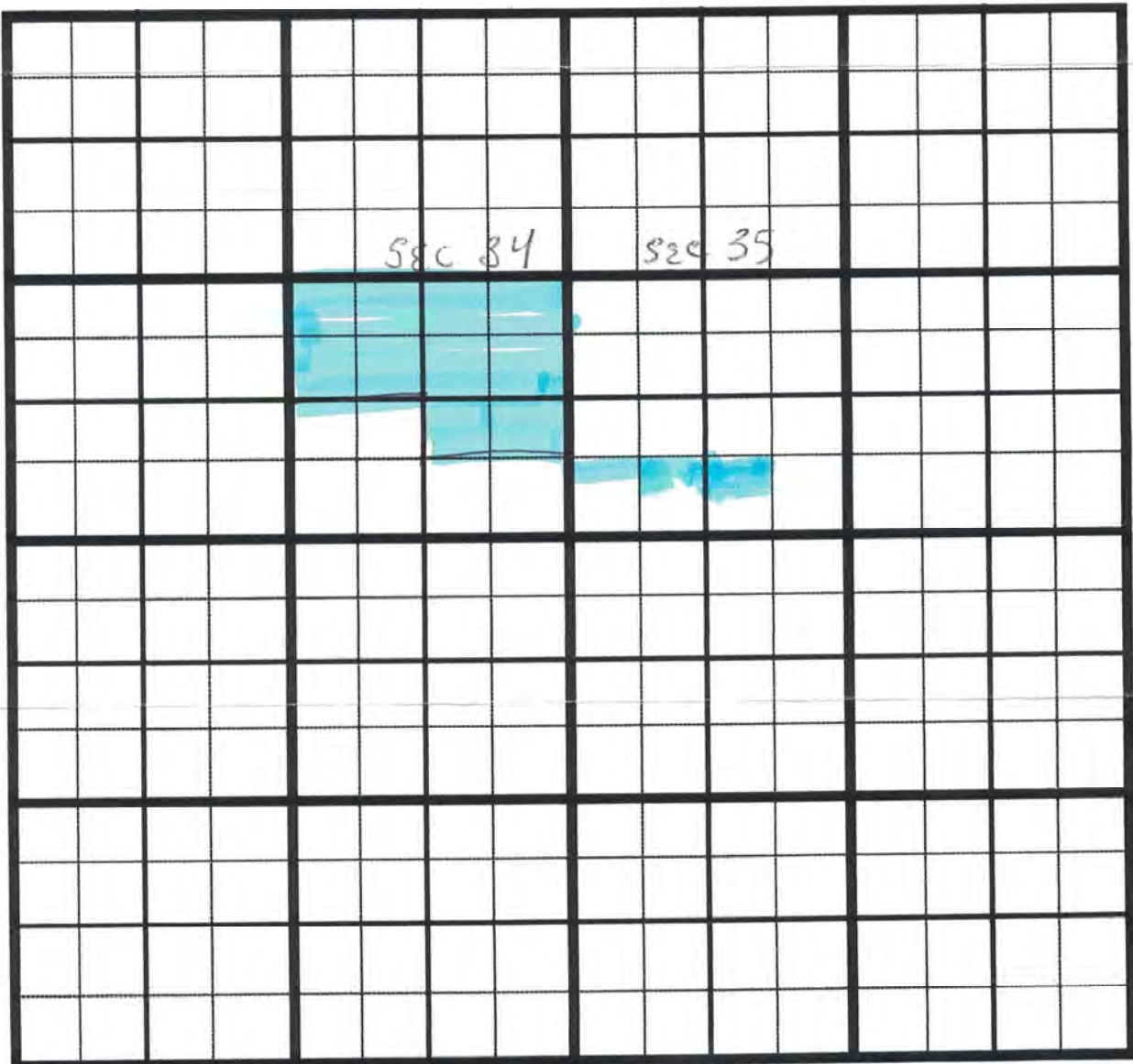
Township Directory
Section Location

Circle Section(s) in Preserve

6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36



NORTH

W
E
S
T

Scale in miles

0

1

SOUTH

3

4

ATTACHMENT 1

WIND TURBINE SAFETY CONSIDERATIONS

Vestas is one of the leading wind turbine manufacturers, with a global share worldwide. Based on its prominence in the world market, its Safety Manual (32 pages) is a credible source of safety information for a well-known manufacturer of wind turbines. Its Safety Manual (13 pages) is considered a credible source of information on the subject of

On page 3 of the Vestas Safety Regulations for Operators at # 2. – Stay and Traffic by the Turbine, Vestas personnel are required to stay a turbine by 400 m (1312 ft) unless it is necessary. Taken into account, they apply to normal operating conditions. (See Exhibit 1)

Under abnormal operating conditions, Vestas expands this to ensure the safety of its employees. This is evidenced by the Vestas Safety Instruction manual for a Falmouth MA wind farm. It addresses the situation of a free spinning “runaway turbine” and states that there are for no one to be allowed within a 1640 feet (500 m) radius

The Nordex Safety Manual also addresses safety in the context of under section 9.3 Fire, it states:

DANGER FALLING TURBINE PARTS In case of a fire in the turbine, parts may fall off the wind turbine. In case of a fire, nobody is allowed to be within 500 m from the turbine. (See Exhibit 3)

Given that these standards apply to employees who are familiar with the implications of wind turbines and are equipped to deal with the consequences, it is indefensible, from a safety perspective alone, to specify in a regulation that would protect the public health, safety and welfare a setback that is



Revision 04 / 2011-07-18

The WT itself is adequately protected against damage by comp measures. However, persons inside or in the proximity of a W proceed as in a grid failure ■ Leave and lock the WT ■ Wait a until the thunderstorm has passed Do not re-enter the WT until

9.3 Fire

DANGER

FALLING TURBINE PARTS

In case of a fire in the nacelle or on the rotor, parts may fall of fire, nobody is permitted within a radius of 500 m from the t

NOTE The WT is equipped with ABC powder fire extinguish. At least one fire extinguisher is located in the tower base near nacelle near the Topbox. This makes it possible to extinguish l well as fires in electrical systems of up to 1,000 V. These fire t for extinguishing a fire on the high-voltage elements, see Chap voltage switchgear or transformer".

9.3.1 Fire in the WT

■ Remove any persons from the danger area ■ If possible, disc the grid ■ Fight the fire with available means if there is any ch cannot be extinguished or if there is no chance of success, call the responsible Remote Monitoring

Item no: 960314 R5 Date 2006-09-11

Issued by: Technology Class: II

Type: MAN Page 3 of 32

Safety Regulations for Operators and Technicians

V90 – 3.0MW/V100 – 2.75MW

Vestas Wind Systems A/S · Alsvej 21 · 8900 Randers · Denmark · www.vestas.com

1. Introduction

A turbine connected to the grid implies certain elements of risk, requiring exercising proper caution.

For safety reasons, at least two persons have to be present.

The work must be properly carried out in accordance with the instructions in the manuals. This implies, among other things that personnel must be familiar with relevant parts of this manual.

Furthermore, personnel must be familiar with the contents of the "Safety Materials" regulations.

Caution must especially be exerted in situations where measures are taken in junction boxes that can be connected to power.

Consequently the following safety regulations must be observed.

2. Stay and Traffic by the Turbine

Do not stay within a radius of 400m (1300ft) from the turbine when it is operating. If you have to inspect an operating turbine from the ground, stay at a safe distance from the plane but observe the rotor from the front.

Make sure that children do not stay by or play nearby the turbine foundation. The access door to the turbine must be locked in order to prevent unauthorized persons from stopping or damaging the turbine controller.

3. Address and Phone Number of the Turbine

Note the address and the access road of the turbine in case of an emergency should arise. The

address of the turbine can often be found in the service report or on the map to the ground

controller. Find the phone number of the local life-saving service.

Vestas Confidential - Falmouth

WQ 1000711-04 EN
Issued by: Technology
Type: Work instruction

Health & Safety Instruction

2.6.1 Special vehicles

Important: *Protect the environment: stop engines when vehicles are not in use.*

- Drivers of special vehicles, such as extra wide or high vehicles, must agree with the supervisor/site manager who will advise as to the risks.
- The supervisor/site manager will also arrange for auxiliary vehicles, if needed.

2.7 In Case of Runaway Operation

A runaway operation is almost impossible, as it would require several minutes.

- If a runaway operation should occur, the plant must be evacuated immediately. Access to the surrounding area in a radius of at least 500 metres must be restricted.

**Vestas advises to “evacuate by route
...access to the surrounding area
at least 500 meters [1640 ft.] must
be restricted.”**

This action is brought in the County of Wyoming because of designation made by Plaintiff.

DATED: Buffalo, New York
August 1-,2014

LIPPES & LIPPES
Office and Post Office Address
1109 Delaware Avenue
Buffalo, New York 14209
(716) 884-4800
Attorneys for Plaintiff

Plaintiffs,

vs. COMPLAINT

INVENERGY LLC Index No.:
One South Wacker Drive
Suite 1900
Chicago, IL 60606

Defendant.

FACTS

The following paragraphs represent the entirety of the complaint before the Court with the exception of paragraphs 1 - 30. The omitted paragraphs list the names and addresses of the Plaintiffs.

31. Upon information and belief, Defendant Invenergy LLC ("Invenergy"), was and is a domestic corporation, authorized to do business in the State of New York.

32. Upon information and belief, the Defendant Invenergy, has its primary office located at One South Wacker Drive, Suite 1900, City of Chicago, State of Illinois.

33. Upon information and belief, Defendant Invenergy created and owns a wind energy operation, including wind turbines on property located within 800-1500 feet from the properties owned by Plaintiffs.

34. Upon the construction of and operation of the wind turbines, Defendant has destroyed Plaintiffs' rural viewshed from their property.

35. Upon the construction of and operation of the wind turbines, Defendant has

caused constant noise, vibrations and flicker to enter Plaintiffs' property, significantly impacting the health and wellbeing of the Plaintiffs and causing them to become sick, sore, lame and disabled.

36. Upon the construction of and operation of the wind turbines, Defendant has caused constant noise and vibrations significantly diminishing the value of Plaintiffs' property and home.

37. Upon information and belief, Defendant's wind turbines have violated, on a regular basis, town noise ordinances that restrict the noise levels to 50 decibels.

38. Moreover, Defendant's operation of such wind turbines caused noise pollution, vibrations, and flicker to occur, creating a nuisance and interfering with Plaintiffs' exclusive possessory interest in their property, and causing Plaintiffs' quality of life to be significantly diminished.

39. In spite of being informed of the nuisance condition created by the Defendant, the Defendant has refused to either abate the nuisance or otherwise engage in any mitigating measures, intentionally continuing the nuisance that they have created, causing a significant diminishment of the Plaintiffs' use and enjoyment of their property, quality of life, health, value of Plaintiffs' property and economic wellbeing.

AS AND FOR A FIRST CAUSE OF ACTION: TRESPASS

40. Plaintiffs repeat and reallege each and every allegation set forth in paragraph "1" through "39" inclusive of this Complaint with the same force and effect as set forth in total herein.

41. Defendant has intentionally caused noise pollution, vibrations, and flicker to enter Plaintiffs' property, causing Plaintiffs to become sore, sick, lame and disabled, diminishing Plaintiffs' property value, and interfering with Plaintiffs' exclusive possessory interests in their property.

42. By reason of the foregoing, Defendant has caused and continues to cause a trespass upon Plaintiffs' property and has interfered and continues to interfere with Plaintiffs' exclusive possessory interests in their property.

43. By reason of the foregoing, Defendant has caused damage to Plaintiffs' real property as well as causing a loss in value of Plaintiffs' property and has adversely affected Plaintiffs' health, wellbeing, and quality of life.

44. Wherefore, Plaintiffs seek damages as indicated in the Ad Damnum Clause of this Complaint.

AS AND FOR A SECOND CAUSE OF ACTION: NUISANCE

45. Plaintiffs repeat and reallege each and every allegation set forth in paragraph "1" through "44" inclusive of this Complaint with the same force and effect as set forth in total herein.

46. By reason of the actions and omissions of the Defendant alleged herein, Defendant has created a nuisance that has substantially interfered with the use, enjoyment and value which Plaintiffs are entitled to in their property and has diminished Plaintiffs' health, wellbeing, and quality of life.

47. Defendant's interference with the property of Plaintiffs continues to this day.

48. Defendant's interference with the property of the Plaintiffs was and is unreasonable in character.

49. Wherefore, Plaintiffs seek damages as indicated in the Ad Damnum Clause of this Complaint.

AS AND FOR A THIRD CAUSE OF ACTION: NEGLIGENCE

50. Plaintiffs repeat and reallege each and every allegation set forth in paragraph "1" through "49" inclusive of this Complaint with the same force and effect as set forth in total herein.

51. At all times herein mentioned, Defendant knew or in the exercise of reasonable care should have known that its actions and activities were done in such a manner to cause damage to the Plaintiffs' health, quality of life, and property.

52. At all times herein mentioned, Defendant knew or in the exercise of reasonable

care should have known, the actions and activities carried out on its property or during its business operation would cause excessive noise, vibration, and flicker effect to surrounding homes and properties.

53. Defendant has a duty to conduct its activities in a manner as to not cause material and substantial annoyance and harm to its neighboring properties and their persons and in their enjoyment of their properties.

54. Defendants, by its methods and use of operations of its business, did materially breach that duty, which continues to this day.

55. The aforesaid occurrence was not caused or due to the carelessness or negligence on the part of the Plaintiffs.

56. Defendant owed Plaintiffs a duty of reasonable care in the manner in which it operated its wind energy activities, fell below such standard of reasonable care, and as a result of the foregoing Plaintiffs sustained damage to their health, property, and their quality of life has been diminished.

57. Moreover, as a result of the foregoing, Plaintiffs have sustained a diminution in their real property value.

58. Wherefore, Plaintiffs seek damages as indicated in the Ad Damnum Clause of this Complaint.

AS AND FOR A FOURTH CAUSE OF ACTION: RES IPSA LOQUITUR

59. Plaintiffs repeat and reallege each and every allegation set forth in paragraph "1" through "58" inclusive of this Complaint with the same force and effect as set forth in total herein.

60. At all times herein mentioned, Defendant knew that its actions and activities in installing and operating wind turbines adjacent to the properties of Plaintiffs would cause damage to Plaintiffs and their properties.

61. The wind turbines were and are under the exclusive care and control of the Defendant.

62. The aforesaid occurrence did in fact result in Plaintiffs' diminished value in property, and adversely affected Plaintiffs' health, wellbeing, and quality of life.

63. As a direct and proximate result of Defendant's negligent, careless and reckless actions, Plaintiffs sustained damage to their real property, economic wellbeing, and their quality of life has been diminished.

64. Wherefore, Plaintiffs seek damages as indicated in the Ad Damnum Clause of this Complaint.

AD DAMNUM CLAUSE

WHEREFORE, Plaintiffs demand judgment against the Defendant as follows:

1. The sum of \$20,000,000.00 to compensate the Plaintiffs for their personal injuries, lost quality of life and loss in property value;
2. The sum of \$20,000,000.00 as punitive damages;
3. The costs of this action;
4. Any such further and other relief that the Court may deem just and proper.

RICHARD J. LIPPES, ESQ.

LIPPES & LIPPES



Orangeville Invenergy Complaint

Download file (<http://s3.amazonaws.com/windaction/attachments/2614/Orangeville-Invenergy-Complaint.pdf>) (2.69 MB) pdf

BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

**IN THE MATTER OF THE
APPLICATION OF DEUEL HARVEST
WIND ENERGY LLC FOR A PERMIT
OF A WIND ENERGY FACILITY AND
A 345-KV TRANSMISSION LINE IN
DEUEL COUNTY**

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**CHRISTINA KILBY'S RESPONSES
TO STAFF'S FIRST SET OF DATA
REQUESTS TO INTERVENORS**

EL18-053

Below, please find Intervenor Christina Kilby's Responses to Staff's First Set of Data Requests.

- 1-1) Provide copies of all data requests submitted to or by you and copies of all responses provided to those data requests. Provide this information to date and on an ongoing basis.

These will be provided.

- 1-2) Refer to SDCL 49-41B-22.

- a. Please specify particular aspect/s of the applicant's burden that you intend to personally testify on.

I intend to personally testify that:

- 1) Deuel Harvest is unable to meet its burden of proving it will comply with all applicable laws and rules;**
- 2) Deuel Harvest cannot meet its burden of proving that the facility will not pose a threat of serious injury to the environment, economic conditions of inhabitants; and**
- 3) Deuel Harvest cannot meet its burden of proving that the facility will not substantially impair the health, safety, and welfare of the inhabitants.**

There is significant evidence, evidence that continues to build about the harms caused by industrial wind turbines: harms from the noise, infrasound, sleep deprivation, dangers of ice throw and fire.

Deuel Harvest must prove that the project will not substantially impair health, safety, and welfare, or pose a threat of serious injury. It is not the Intervenor's burden to prove harm from the project. Deuel Harvest must present scientifically sound evidence proving that turbines and the noise and infrasound they produce will not substantially impair the health, safety, and welfare of the inhabitants, nor pose a threat of serious injury to the

environment, and economic conditions of inhabitants. I do not believe Deuel Harvest will be able to meet its burden.

See attached studies and reports served simultaneously. More may follow.

- b) Please specify particular aspect/s of the applicant's burden of proof that you intend to call a witness to testify on.

Unknown at this time.

- 1-3) Refer to SDCL 49-41B-25. Identify any “terms, conditions, or modifications of the construction, operation, or maintenance” that you would recommend the Commission order. Please provide support and explanation for any recommendations.

I ask that setbacks for non-participating landowners be set at two miles with the option of a waiver. This is because of the characteristics of and problems caused by infrasound that turbines are known to produce.

As an alternative to two-mile setbacks, sound levels should not be allowed to exceed any level that can cause sleep disturbance, annoyance, or stress. Nonparticipating landowners should not be forced to sacrifice their enjoyment, comfort, or health for the profits of the applicant.

I feel Deuel Harvest should be required to pay for independent testing of sound and infrasound at all residences both prior to construction, and again when the project is fully operational to ensure compliance.

I feel upon any reliable complaint made to a PUC liason, Deuel Harvest should be required to shut down the possibly offending turbine until an independent test done at Deuel Harvest’s expense can prove no violation exists.

I ask that I be allowed to modify these requests later as I become of aware of new information.

- a. Specifically, what mitigation efforts would you like to see taken if this Project is constructed.

I believe the only effective solution to the problems created by turbines is setbacks sufficient to prevent the loss of enjoyment of the property. I believe property owners have the right to the quiet enjoyment of all of their property, so setbacks should be from property lines. I do not think landowners should have to sacrifice the enjoyment of their property to maximize profits to Invenergy. Mitigation is not sufficient. Long term and continuous harassment and health effects from noise, flicker and infrasound is unjustified and a serious harm. It should not be allowed.

- 1-4) Please list with specificity the witnesses that you intend to call. Please include name, address, phone number, credentials and area of expertise.

Unknown at this time.

Do you intend to take depositions? If so, of whom?

Unknown at this time, but it is unlikely because of time constraints.

Dated this 26th day of February 2019.

/S/ Christina Kilby
Christina Kilby
Intervenor
112 Geneva Blvd.
Burnsville, MN 55306
christinaLkilby@yahoo.com

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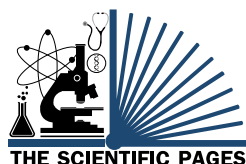
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Research Article

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Occupational and Residential Exposures to Infrasound and Low Frequency Noise in Aerospace Professionals: Flawed Assumptions, Inappropriate Quantification of Acoustic Environments, and the Inability to Determine Dose-Response Values

Mariana Alves-Pereira^{1*} and Huub HC Bakker²

¹School of Economic Sciences and Organizations, Lusófona University, Portugal

²School of Engineering and Advanced Technology, Massey University, New Zealand

Abstract

Professionals within the aerospace industry are often required to remain within acoustic environments characterized by a predominance of low frequency and infrasound components. Safety-and-health-in-the-workplace officials are mindful of the threat these extreme environments can pose to the hearing function. Noise-exposed professionals are, therefore, frequently provided with a plethora of ear protection devices to shield this vital human sense. The vast majority of noise-protection guidelines and regulations, however, are inappropriate to protect aerospace professionals against acoustic environments rich in Infrasound and Low Frequency Noise (ILFN) because they are based on the flawed premises that ILFN only affects humans through the aural pathway, and that dynamics are unimportant. Consequently, the numerical values needed to estimate potential harm to people (dose-response levels) are not routinely obtained or assessed. The goals of this paper are to inform a) Aerospace professionals who are consistently exposed to acoustic environments rich in ILFN, about how this agent of disease is being incorrectly evaluated leading to improper worker protection; and b) Noise control and health professionals who work within the aerospace industry, about new methodologies in acoustical evaluations pertinent to infrasound and low frequency noise dose-response values. New sources of ILFN are increasingly present in the vicinity of residential environments, quite possibly eliminating biological recovery periods for noise-exposed aerospace workers. This paper details the inadequacy of the use of the dBA metric and 1/3-octave-band analysis when protecting workers (and the public) against excessive ILFN exposures. The complexities associated with acoustical evaluation in conjunction with objective and pertinent medical outcomes are discussed, and the need for narrowband analyses in routine evaluation procedures is emphasized.

Keywords

Infrasound, Low frequency noise, dBA, Narrow-band analysis, Occupational exposure, Environmental exposure, Pathology

Introduction

In a widely read paper published by the World Health Organization (WHO), *Burden of disease from environmental noise* [1], the long-term effects of excessive noise exposure were shown to be worrisome, at best. Historically, noise exposures were deemed to be detrimental to the hearing function, i.e., people exposed to loud noise were more likely to become deaf, or hearing impaired. Consequently, only a portion of the acoustical spectrum was focused upon - the one containing the frequencies responsible for hearing loss.

This restricted segment of the acoustical spectrum, called 'the audible portion', ranges from 20 Hz to 20

kHz. Within this wide range of frequencies, though, not all of them are equally responsible for deafness or

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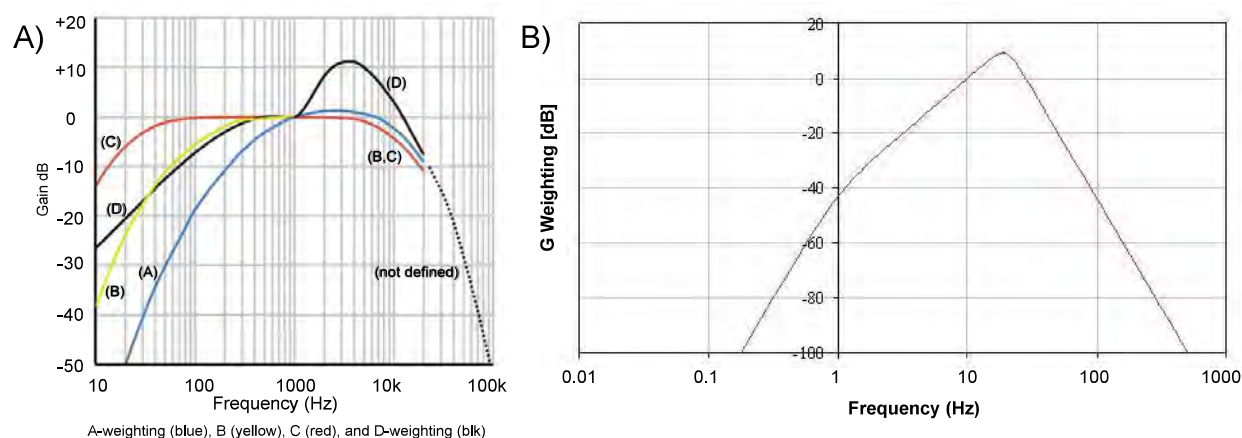


Figure 1: Acoustic Weighting Curves A) Weighting curves for A-weighting (A), B-weighting (B), C-weighting (C) and D-weighting (D) [40]. B) G-weighting Curve [41].

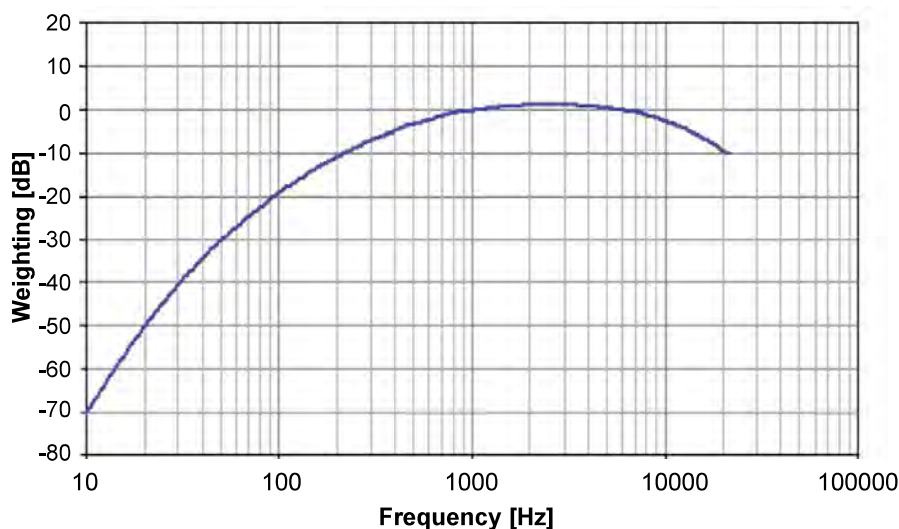


Figure 2: Frequency Response Curve for the A-weighting Network at 10 Hz, well within the ILFN region, the error is approximately a 70 dB reduction, i.e., what is measured is 70 dB less than what is actually present in the environment [42].

hearing loss. Deafness due to excessive noise exposure is predominantly a consequence of loss of hearing function within the 250-8000 Hz range, i.e., deafness at frequencies above 8000 Hz or below 250 Hz is not as relevant for speech intelligibility as are those contained within the 250-8000 Hz range. Health-related acoustical evaluations were thus urged to focus on this particular range of frequencies. This required measuring instrumentation that would eliminate all the frequencies considered irrelevant to human hearing impairment, i.e., all extending beyond the 250-8000 Hz range. Infrasound and Low Frequency Noise (ILFN) (< 200 Hz) was, therefore, deemed irrelevant for the purposes of protecting human health.

The human ear responds to sound non-linearly, both in terms of frequency and sound pressure level. Hence the

development of filters (with specific frequency-weighting curves) designed to simulate the non-linear sensitivity of human hearing. Measuring sound levels with one of these filters would then better represent the human perception of the sound. Figure 1 shows examples of A-, B-, C- and D-weighting curves (Figure 1A), and the more recent G-weighting curve, developed for ILFN-rich environments (Figure 1B).

Under the dBA metric, acoustical energy contained in other portions of the spectrum are de-emphasized (< 250 Hz and > 8000 Hz) or deemed irrelevant for evaluation (< 20 Hz, or 'infrasound', and > 20 kHz, or 'ultrasound'). Regulations have been guided by these principles, leading to the ubiquitous capture of information within the restricted segment of the acoustical spectrum (20 Hz - 20

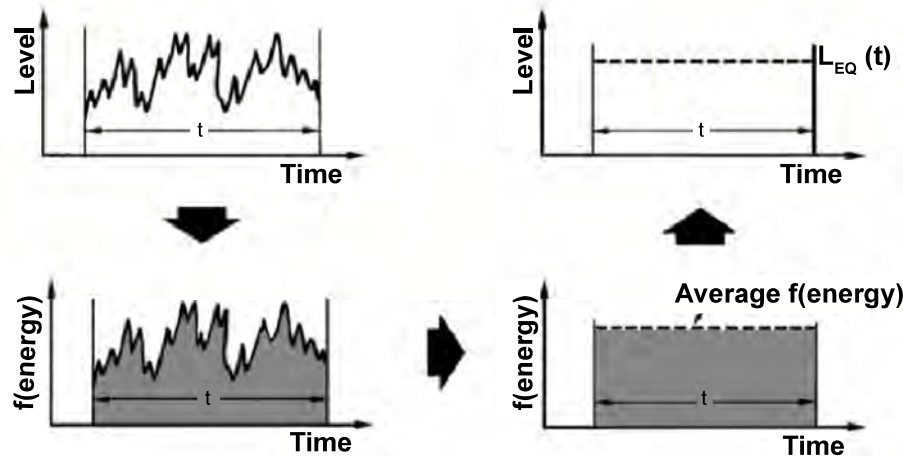
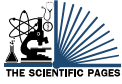


Figure 3: Mathematical treatment applied to a time-varying signal. The resulting, constant L_{eq} value represents the same amount of energy (area in grey under the curve) contained in the original time-varying signal [43].

kHz), and with the A-weighting being applied. **Figure 2** shows the frequency response curve for the A-weighting filter, which is relatively flat between 800 - 8000 Hz. When measuring frequencies < 200 Hz with an incorporated A-weighting network, the numerical value obtained for the sound pressure level presents with a 10 to 70 dB error. While the A-weighting system seems to yield good results for hearing protection, it is clearly inadequate for assessing the amount of acoustical energy present in the ILFN ranges, because these lower frequency components are discounted; for example, a reduction of about 70 dB at 10 Hz (**Figure 2**).

Two additional difficulties exist when evaluating acoustic environments: a) They are constantly varying in time (seconds); and b) They do so continuously across the entire acoustical spectrum. Hence, to enable analyses, both time and frequency parameters need to be segmented. To transform a time-varying signal into some manageable number, the concept of time-averaged sound level was developed (L_{eq}). **Figure 3** sketches the mathematical treatment given to a time-varying signal, such as an airborne pressure wave.

Occupational and health issues consider long term exposures in L_{Aeq} (A-weighted, time-averaged sound level), and allow short testing samples as representative of an 8-hour day exposure. Many environmental regulations, on the other hand, mandate 10-minute time averages of L_{Aeq} , so that values are not skewed by intermittent loud sounds. Either way, information on the dynamic, time-dependent portion of the acoustic environment is diluted when the signal has significant variations in time and is segmented into 10 min or 1 hour windows.

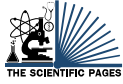
The 'audible' frequency spectrum was segmented into 'octave' and '1/3-octave' bands, facilitating further analyses for noise control evaluations. Although data resolu-

tion was improved with the 1/3-octave bands analyses, this methodology still only provides a crude resolution of the acoustic environment. **Figure 4A** compares octave band and 1/3-octave band measurements. In the pre-digital era, investigations of finer resolution were very involved, complex and beyond the means of general acoustic investigations.

When no weighting network is incorporated into the acoustic signal capture, measurements are un-weighted (unfiltered), and the metric written as dBLin (linear) to distinguish it from other forms of deciBel. **Figure 4B** shows the difference between the overall dBA and dBLin levels in an environment where ILFN components are predominant. While the overall dBA level reflects what a human would hear, the dBLin level reflects the acoustical energy to which the body is exposed.

There are further limitations related to accuracy when the frequency spectrum is segmented into 1/3-octaves. This method ignores the exact problem that impulsive sounds (perceived as irritating or not) will be invisible in such L_{Aeq} measures. For example, a single gunshot would have little, if any, impact upon a 10 minute dBA-level average but would hardly fail to wake a sleeper. In terms of urban population health, the inappropriateness of using the dBA metric to assess ILFN-rich environments was recognized almost two decades ago by the WHO: "When prominent low-frequency components are present, measures based on A-weighting are inappropriate. However, the difference between dBC (or dBLin) and dBA will give crude information about the presence of low-frequency components in noise" [2].

It is not uncommon to address the maximum dBC level or dBLin level in order to 'squeeze out' more acoustical information from measurements obtained with leg-



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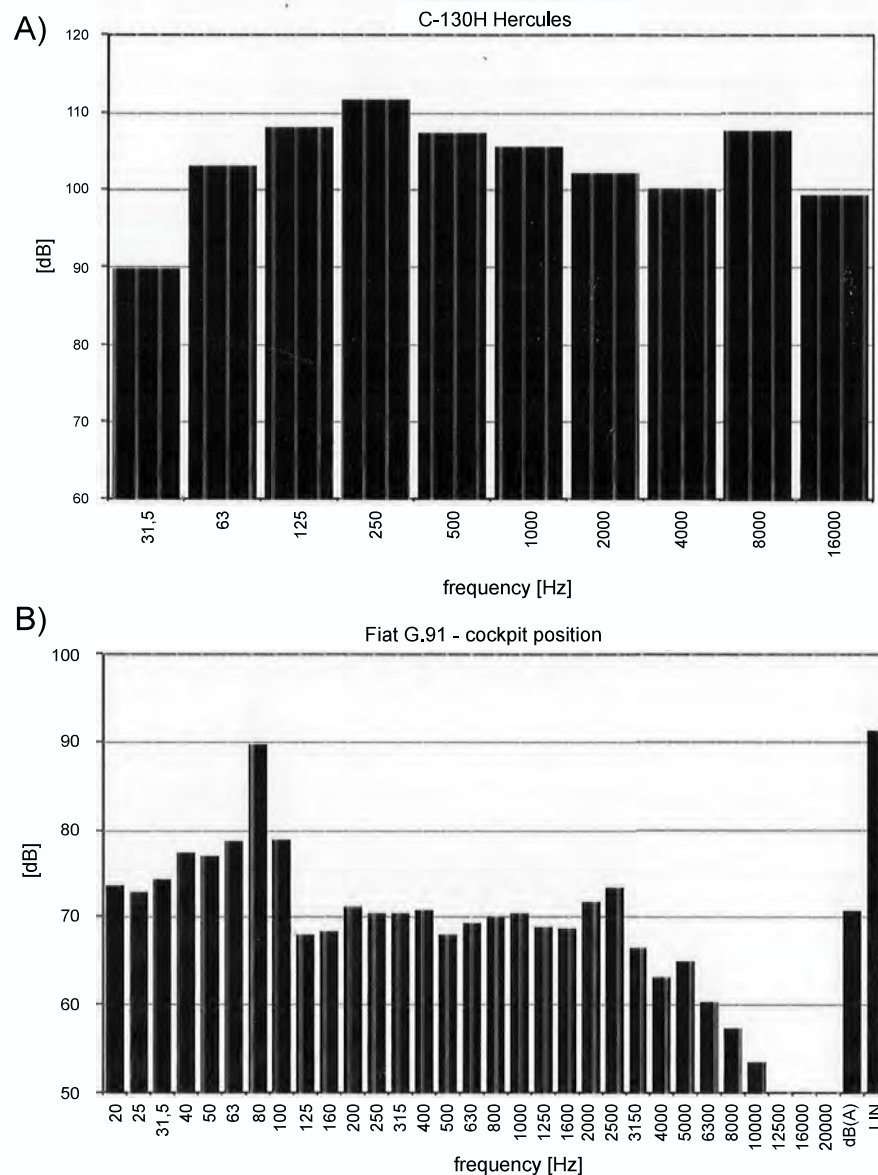


Figure 4: A) Octave band frequency distribution analysis radiated by a C-130 Hercules at normal power setting [44]; B) 1/3-octave band frequency distribution analysis inside the Fiat G-91 cockpit. The two bars on the right indicate the dBA and dBLin levels, respectively. The much lower dBA level when compared to the dBLin level reflects the numerical reduction imposed by the A-weighting Network [45].

isolated methodologies. However, a more detailed numerical characterization of acoustic environments within the ILFN range is needed, in order to establish dose-response values for human protection.

Interface between acoustical phenomena and the human body

The WHO publication *International Classification of Diseases* (ICD-10 2016) [3], dedicates Chapter 20 to “External causes of morbidity and mortality”, and block W20-W49 refers to “Exposure to inanimate mechanical

forces”:

W42 - Exposure to noise Incl.: Sound waves, Supersonic waves

W43 - Exposure to vibration Incl.: Infrasound waves [3].

Airborne acoustical phenomena interact with the human body when mechanical coupling occurs between the oncoming mechanical force and a particular tissue or tissue system of the human body. This brings the issue of ILFN health effects into the field of materials engineering. Biological tissues are viscoelastic materials, i.e., they



possess the properties of creep, relaxation and hysteresis^a. Moreover, they feature anisotropy, i.e., equal forces applied in different directions yield different results. Biological material, particularly when considering whole-body effects, cannot be modeled as a simple Hookean elastic^a; and neither can its response when immersed in an ILFN-rich environment.

Prof. Donald Ingber (Wyss Institute, Harvard University), proposed decades ago that animal cells were constructed in accordance with principles of tensegrity [4-6], i.e., architectures consisting of elements providing continuous tension, and elements providing discontinuous compression [7]. By modeling the cell as a tensegrity structure instead of the prior, elastic continuum model, it was possible to begin to understand cellular mechanotransduction, i.e., inter- and intra-cellular communication established via mechanical signals, as opposed to biochemical signals [8,9 for example]. Mechanotransduction and cellular tensegrity architectures are essential to understanding the specific structural changes in ILFN-exposed cells, as seen through light and electron microscopy [10-12]. These mechanically-induced cellular effects are not accounted for under current noise protection legislation, guidelines and procedures, as they do not respond to acoustical energy via the aural-perception pathway.

Mechanical coupling between airborne pressure waves and the human body is known to occur at the ear; the design of which is an engineering marvel. Mechanical coupling between airborne pressure waves and other regions of the body are acknowledged to exist only if the acoustic energy is at sufficient amplitude (i.e., if the event is perceivable by human senses), otherwise, effects are (perhaps erroneously) considered to be irrelevant or non-existent.

The response of biological tissue to ILFN is frequen-

cy-dependent. An early example is a study conducted in 1969 (within the scope of the Soviet and US space programs), where dogs were exposed to ILFN-rich environments at sound pressure levels ranging from 105 to 155 dB. This induced multiple hemorrhages in the lung tissue that “never exceeded 3 mm in diameter” [13]. Increasing the dB-level of the environment did not increase the size of the hemorrhagic areas, but rather, their number. In the early 1990’s, Professors Nekhoroshev and Glinchikov (St. Petersburg Academy of Sciences, Russia) exposed laboratory animals to infrasound (8-16 Hz) at 120-140 dB, for 3 hr daily, for 1, 5, 10, 15, 25, and 40 days, and found different morphofunctional changes in the cellular structures of myocardium and liver tissues when compared to controls [14,15]. These changes varied with frequency, exposure time and exposure level. For the past three decades, another team led by pathologist Col. Castelo Branco (Portuguese Air Force), has systematically studied both workers and animal models exposed to ILFN. As a result, the clinical evolution of the signs and symptoms consistently observed in aeronautical technicians was established in 1999 [16], supported by numerous collateral studies in human populations and animal models in subsequent years [17-19]. Since then, this ILFN-induced pathology, (termed Vibroacoustic Disease - VAD), has also been identified (as per objective clinical testing) in residential settings [20-22].

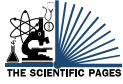
Certain, narrow frequency ranges can elicit a specific response from one type of tissue and not another, located adjacently, because each type of material has its own creep, relaxation and hysteresis coefficients^a. Each tissue type also possesses its own mechanical resonance frequency. Hence, at the electron microscopy level of ILFN-exposed tissue, the re-organization of inter- and intra-cellular architectures seem to reflect a mechanical reinforcement required to maintain structural integrity [23,24].

In Workplace Safety, vibration is considered as that which is transmitted into the human body through solid-to-solid contact, i.e., contact with a chain-saw (hand-arm vibration) or a vibrating platform (whole-body vibration). To measure vibration, accelerometers are used instead of microphones. With ILFN, impacts to the human body occur via a different interface: air-to-solid, or rather, air-to-composite viscoelastic material. Modeling human response to ILFN exposure based on solid-to-solid interfaces has not, therefore, proven very successful.

ILFN dose-response values - the need for narrow-band analyses

Dose-responses for ILFN exposures must be frequency dependent if they are to properly protect hu-

^aHookean Elastic vs. Viscoelastic Material. 1) In a Hookean (or purely elastic) material, total deformation depends on total load, and no further deformation occurs even if load is maintained. In viscoelastic materials, however, when stress is applied and maintained, they may continue to further deform, even though stress load remains unaltered. This property is called creep. 2) In a purely elastic material, the strain within the material is constant throughout the application of the load; it does not vary with time, only with the amount of applied stress. In viscoelastic materials, when stress is applied and maintained, strain can decrease with time. This property is called stress relaxation. 3) Consider repetitive or cyclical loads on materials. In purely elastic materials, periodic loads will not alter the stress-strain curve. The pathway taken by the material to deform is exactly the same pathway it takes to return to its original, equilibrium position. In viscoelastic materials, however, the return to equilibrium may be different than the pathway used to get to the point of deformation. (The word pathway is here loosely used, and is meant to encompass all spatial, temporal and energetic components of these types of movements.) This property is called hysteresis.



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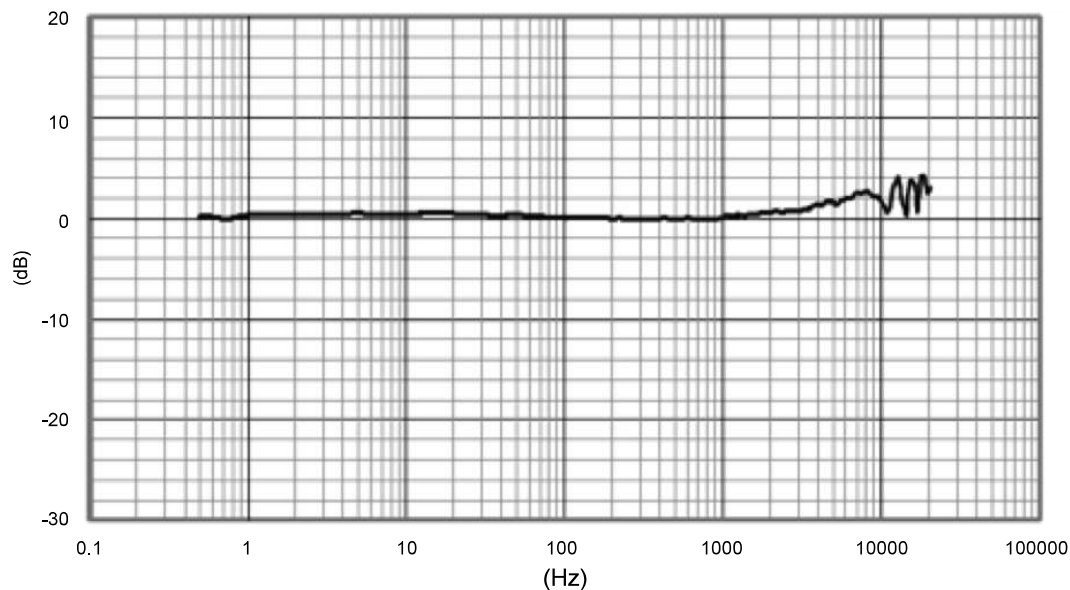


Figure 5: Frequency response curve for the microphones used by the SAM Scribe Mk1 system [29].

mans from excessive exposure to ILFN-rich environments. The determination of dose-responses for ILFN exposure has been scientifically impossible to achieve, however, because the ILFN in itself is not being quantified during routine acoustical evaluations. This is the point where the ILFN-rich occupational and environmental exposures meet. Both require precise ILFN measurements if human populations are to be properly protected from this agent of disease, whether at work or in the home.

For decades, the biomedical world has been in dire need for proper scientific instrumentation to objectively quantify ILFN-rich acoustic environments. Given that current instrumentation discards much of the information that characterizes an acoustic environment (at the behest of regulations) precluding any real scientific analysis, it becomes obvious that current general-sound-level measurement instrumentation is not suited to requirements.

The limitations of dBA methodology and 1/3-octave segmentation with respect to ILFN, can be resolved by the application of analyses using no weighting and by a proper signal capturing of the acoustic environment. This would allow a more precise identification of events that occur within frequency bands that are narrower than the 1/3-octave segmentation, and of periodic signals that occur in the time domain. Narrow band analyses can provide information that would permit the identification of discrete signals (e.g., tones or harmonics) forming acoustic signatures that are not evident with the dBA-1/3-octave methodology [25,26]. This is shown in

the next sections.

Material and Methods

Instrumentation

The equipment used for acoustic capture was a SAM Scribe Full Spectrum (FS) system (Model: Mk1, Atkinson & Rapley, Palmerston North, New Zealand) [27,28]. It consists of a two-channel device that can measure at sampling rates up to 44.1 kHz, and that delivers data streams via USB to a Windows notebook computer, storing it as uncompressed wav files to hard disk. GPS information is also stored as metadata in the files, and this includes a digital signature. The system can accurately record from 0.1-1000 Hz, as per the manufacturer frequency response of the two electrets condenser microphones (custom-made Model No.: EM246ASS'Y, Primo Co, Ltd, Tokyo, Japan), Figure 5 [29].

The SAM Scribe FS unit has two switches: one enables a 1 Hz high-pass filter to remove unwanted 'micro-barom' events^b below 1 Hz, and the other enables a + 20 dB gain boost. All measurements were conducted with the 1 Hz filter enabled and with the 20 dB gain boost disabled. All measurements are reported from 1-800 Hz, and were captured with a sampling rate of 11.025 kHz.

Measurement methodology

^bA 'microbarom' is a transient change in air pressure caused by events such as shutting a door. This can cause the microphone to saturate, causing clipping, and, in any case, is not generally part of the acoustic environment being studied and should not, therefore be included in the analysis.



All measurements were recorded to uncompressed wav file including the required reference calibration tone prior to and after measurements. Calibration tones were produced with a Type I calibrator (part of the SAM Scribe system) at 1000 Hz/94 dB. Calibration of the system rests on the manufacturer's frequency-response curve for the Primo microphone capsule (Figure 5) as well as comparison calibrations between 6.3 Hz and 1000 Hz of the full system against a Larsen-Davis 831 sound level meter with a current National Association of Testing Authorities (Australia) calibration certificate. The manufacturer's frequency response curve shows that the microphone capsule is very close to linear over the 1-1000 Hz range used in this study.

Wind-shields were always placed on both microphones during measurements. Microphones were attached to tripods at approximately 1.5 m above the ground. After microphone positioning and initial calibration, at least three 10 min segments of data were captured at each location. Both microphones were placed at the same location, along the same axis, approximately 20 m apart from each other, as limited by cable distance (5 m + 15 m). One microphone (red) was always placed at approximately 22 m from the shed entrance, and the second microphone (blue) was placed at approximately 42 m from the shed entrance (see below).

Measurements were performed on a rotating basis between locations, and on different days - 16, 30, and 31 December, 2016. This acoustical evaluation is part of an international, citizen-based research effort into the health effects caused by excessive exposure to ILFN, and to which the authors contribute [30]. Within this context field-sites, such as this one, become available due to the efforts of citizen scientists.

Selection of locations

Data was gathered at a farm where the residential home is in the vicinity of the animal sheds (Figure 6). This preliminary data was selected for presentation due to: a) Its pedagogical strength for clarifying the difference between the type of data obtained through narrow-band analyses and legislated methodologies; b) The relative location of the home within the ILFN-rich acoustic environment (Figure 6A); and c) The possibility of gathering clues that may contribute to an explanation of different animal behavior in the presence of anthropogenic ILFN, depending on animal-shed location (Figure 6B).

The anthropogenic sources of ILFN in question are four, 3-MW Industrial Wind Turbines (IWT), 150 m in total height (hub height + $\frac{1}{2}$ blade diameter) [31]. Figure 6A shows the relative positions of the home and animal sheds to the IWTs.

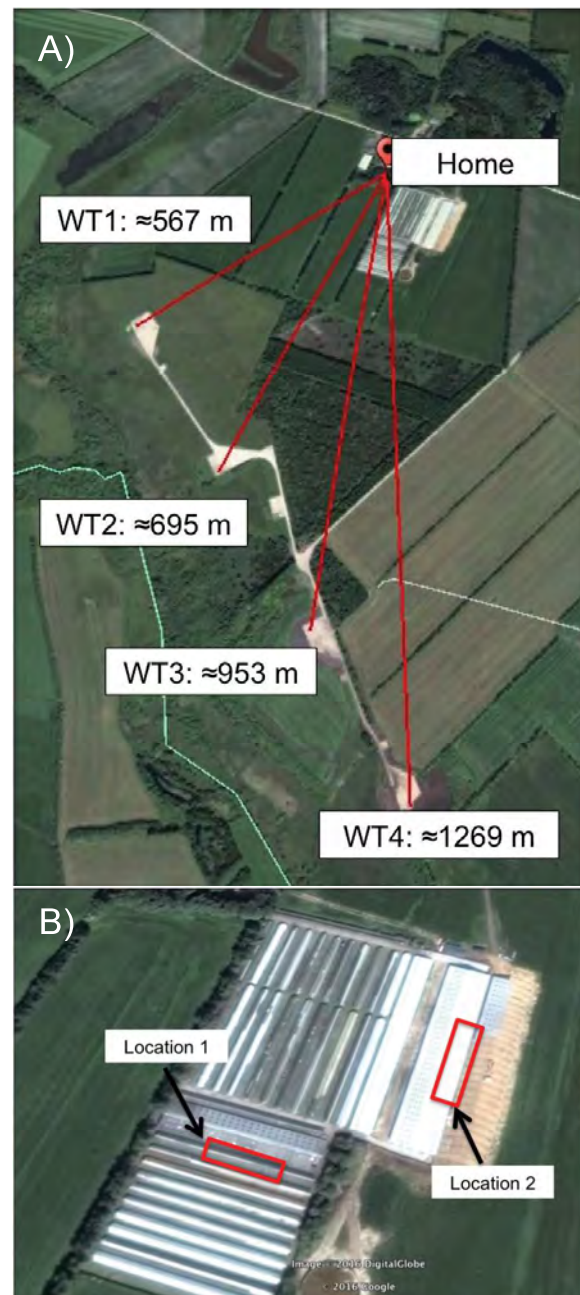
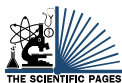


Figure 6: Images reconstructed from Google Earth A) Relative positioning of each of the 4 WT to the residential home and adjacent animal sheds; B) Definition of Location 1 and Location 2.

Locations 1 and 2 were suggested by the property owner as two locations where animal pups responded differently when IWT were rotating. Figure 7 shows the different construction types of the animal sheds in Location 1 and Location 2. Location 1 is a shed of older, wooden construction, with an interior space approximately 2.5 m in height and 75 m in length (Figure 7A). Location 2 is a more modern shed, mostly made of metal,



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Figure 7: Animal shed structures have different constructions styles A) Animal shed of Location 1; B) Animal shed of Location 2.

Table 1: Date and time of acoustical measurements per location.

	Date	Time
Location 1	16 Dec	14:34 - 15:10
	30 Dec	13:25 - 14:02
	30 Dec	17:01 - 18:05
	30 Dec	22:59 - 00:16
	31 Dec	03:28 - 04:37
	31 Dec	08:21 - 09:22
Location 2	16 Dec	15:30 - 16:10
	30 Dec	11:16 - 12:06
	30 Dec	14:11 - 15:28
	30 Dec	20:32 - 21:42
	31 Dec	00:25 - 01:41
	31 Dec	04:40 - 05:58

with an interior space approximately 7.0 m in height, and 110 m in length (Figure 7B). Both contain water-supply systems for the animals that may produce specific and identifiable signatures within the acoustic environment. Since IWT rotation began, the property-owner has opted to maintain his breeding male animals in Location 1 rather than in Location 2. Table 1 tallies the measurements conducted at Location 1 and Location 2 in 2016.

Wind speed

In the case of this anthropogenic ILFN source (IWT), acoustical emissions output depend on the wind speed. (IWT power output graphs concurrent with these measurement sessions are unavailable).

Weather data was obtained from the Danish Meteorological Institute, corresponding to the monitoring tower closest to the farm, approximately 35 km away. Air pressure values were unavailable. Although the lack of *in loco* weather monitoring equipment led to imprecise numerical values, the goal of this data is not to relate specific wind speeds to specific IWT acoustical emissions, but rather to compare ILFN components under two different IWT regimens, at two different locations. Weather data

Table 2: Weather data and IWT operation.

	16 Dec 2016 - Baseline	30 Dec 2016 - ILFN-rich
Wind speed (m/s)	0.5 - 1.5	4.0 - 6.5
Wind direction	south-southwest	southwest
Temperature (°C)	0 - 1	6 - 8
Rel. humidity (%)	90 - 100	90 - 95
Precipitation (mm)	0	< 0.5
IWT rotation	no	yes
Hour of video footage	14:38, 14:42	11:20, 13:30, 15:40

Table 3: Definition of the 10 min measurement segments selected for scrutiny.

Location	IWT Rotation	Location Classification	Date	Time
1	No	Baseline	16 Dec	14:40
	Yes	ILFN-rich	30 Dec	17:30
2	No	Baseline	16 Dec	15:50
	Yes	ILFN-rich	30 Dec	11:20

is given in Table 2.

Results

Acoustic data was processed in Matlab (The Math-Works, USA) using narrow-band filters complying with the ANSI® S1.11-2004 and IEC 61260:1995 standards, as well as FFTs.

Table 3 shows the measurement segments selected for scrutiny.

Figure 8 and Figure 9 show the traditional 1/3-octave spectra and the total dBA and dBLin levels, in Locations 1 and 2 respectively, under baseline conditions. Figure 10 and Figure 11 show the same numerical data but represented as narrow-band analyses.

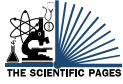
Similarly, Figure 12 and Figure 13 show the traditional 1/3-octave spectra and the total dBA and dBLin levels, in Locations 1 and 2 respectively, under ILFN-rich conditions. Figure 14 and Figure 15 show the same numerical data but represented as narrow-band analyses.

For ease of presentation herein, only the results corresponding to the blue microphone (placed at approximately 42 m from the entrance of the sheds) are presented.

Preliminary analysis

16 - 20 Hz:

Baseline: Both Location 1 and Location 2 exhibit a continuous acoustical phenomenon with strong tonal characteristics occurring at around 16 Hz (Figure 10 and Figure 11). This could be associated with the water systems installed in the shed to feed the animals. Water could distinctly be heard running in the background in Location 1, but less so in Location 2.



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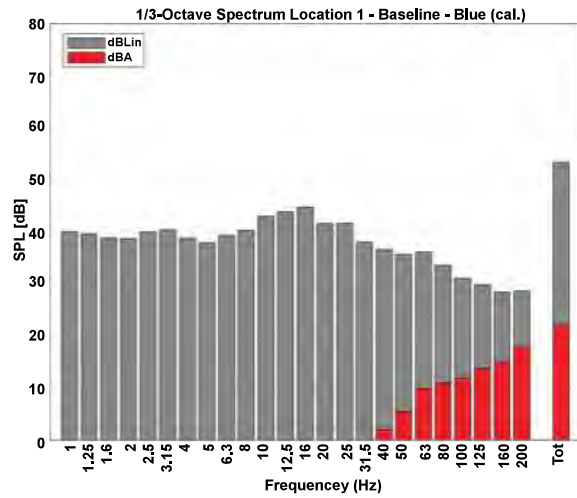


Figure 8: Location 1, Older Shed, at 14:40 on Dec 16. Representative data over a 10-min interval and analyzed between 1-200 Hz.

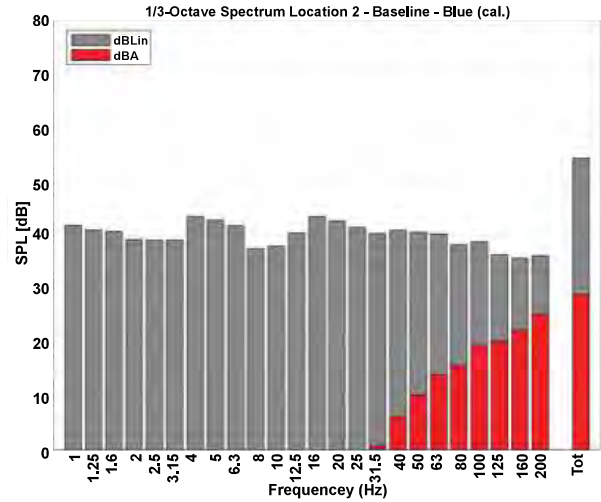


Figure 9: Location 2, Newer Shed, at 15:50, on Dec 16. Representative data over a 10-min interval and analyzed between 1-200 Hz.

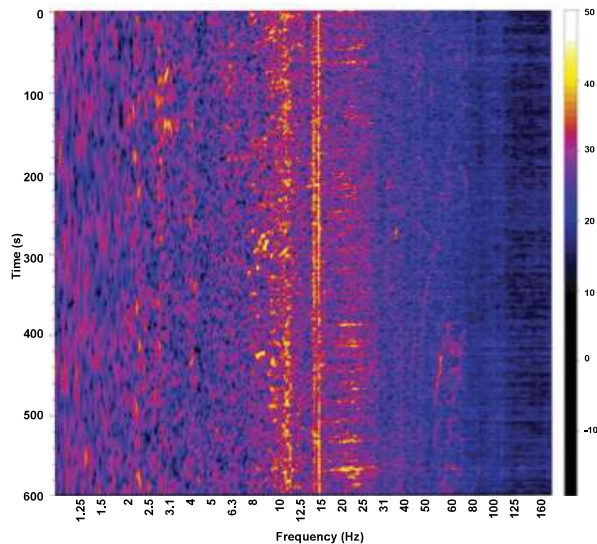


Figure 10: Location 1, Older Shed, at 14:40 on Dec 16. Representative data over a 10-min interval and analyzed between 1-200 Hz.

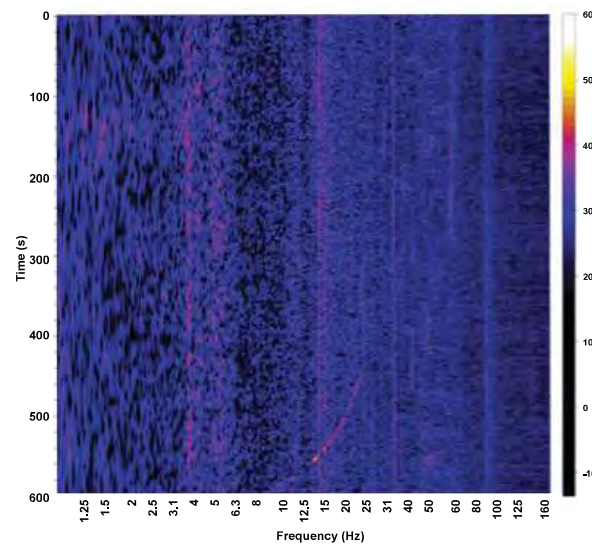


Figure 11: Location 2, Newer Shed, at 15:50, on Dec 16. Representative data over a 10-min interval and analyzed between 1-200 Hz.

ILFN-rich: In Location 1, the continuous acoustical phenomenon, seen at around 16 Hz in the baseline (Figure 10), is still visible in Figure 14, but is no longer distinguishable from other acoustical events in Figure 15 (baseline, Figure 11). The apparent constancy of this acoustical feature in at least three of the four situations seems to suggest some permanent equipment, and hence the animal water supply system is a good contender.

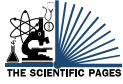
Concurrent with the existence of IWT rotation, a new acoustical phenomenon, not present in either baseline, appears at 20 Hz and in both locations. The non-continuous coloring of this line shows that pressure level was not con-

tinuous. Further analysis (Figure 16 and Figure 17) shows that this 20 Hz phenomenon was equally prominent in Location 2 (newer shed) as in Location 1 (older shed).

10-12.5 Hz:

Baseline: Given the continuous nature of the acoustical event that occurs between 10-12.5 Hz (Figure 10), this might also be associated with the operational water systems, or other equipment necessary to maintain the animals.

ILFN-rich: Below 12.5 Hz, both locations see an increase in their acoustical energy.



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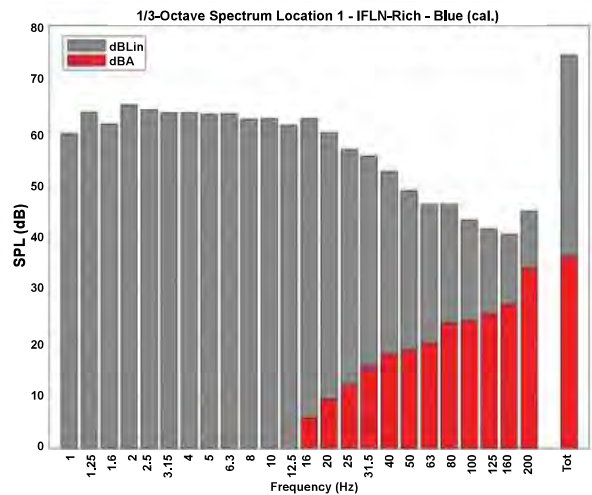


Figure 12: Location 1, Older Shed, at 17:30 on Dec 30. Representative data over a 10-min interval and analyzed between 1-200 Hz.

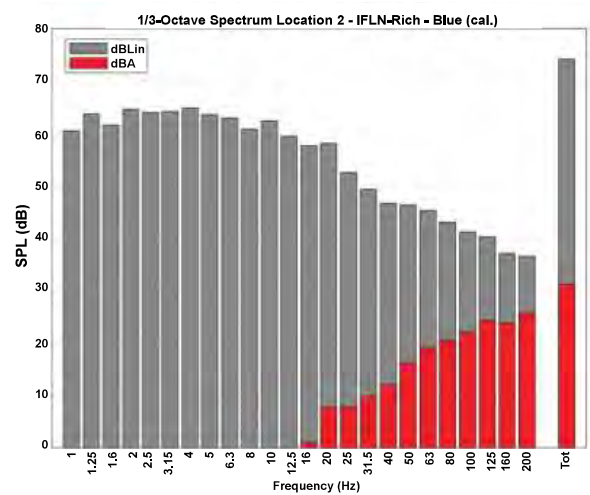


Figure 13: Location 2, Newer Shed, at 11:20, on Dec 30. Representative data over a 10-min interval and analyzed between 1-200 Hz.

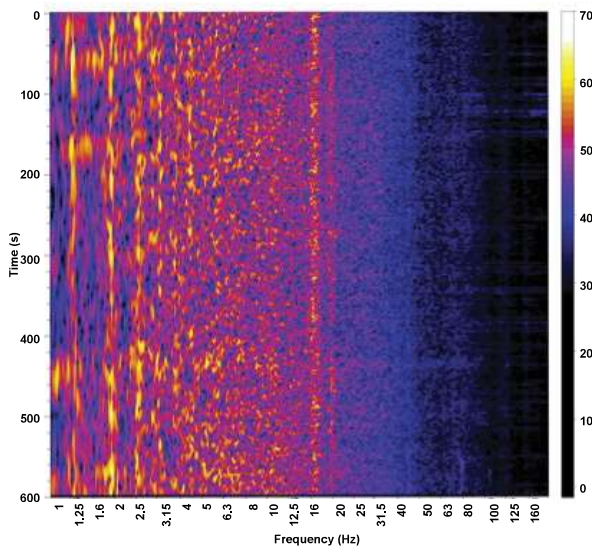


Figure 14: Location 1, Older Shed, at 17:30 on Dec 30. Representative data over a 10-min interval and analyzed between 1-200 Hz.

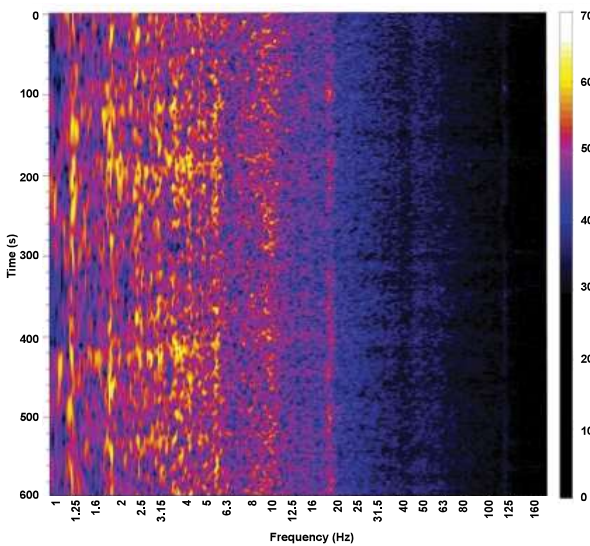


Figure 15: Location 2, Newer Shed, at 11:20, on Dec 30. Representative data over a 10-min interval and analyzed between 1-200 Hz.

< 5 Hz:

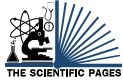
Baseline: In Location 2, the continuous phenomena occurring between 4-6.3 Hz could be related to the newer water supply system. ‘Spurts’ of acoustical energy are visible at the lowest frequency ranges (≤ 2 Hz), in both locations but seemingly more prominently in Location 1 (Figure 10). The source of these ‘spurts’ is, as yet, unknown.

IFLN-rich: The continuous acoustical phenomena occurring at 4-6.3 Hz in Location 2 during baseline (Figure 11) is no longer visually distinguishable in Figure 15.

The ‘spurts’ of acoustical energy identified at ≤ 2 Hz in both Locations during baseline, are only vaguely visible in the IFLN-rich situation. In this lowest range of frequencies, both locations still seem to exhibit acoustical phenomena in spurts but, now, some of them contain more acoustical energy (Figure 14 and Figure 15).

dBA methodology:

Baseline: Location 2 exhibits a higher total dBA level (44.9 dBA) (Figure 9 and Table 4) than Location 1 (38.6 dBA) (Figure 8 and Table 5). While this seems to be opposite of what is seen in the respective sonograms (Figure



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10 and Figure 11), it must be recalled that dBA emphasizes acoustical phenomena that occur above 200 Hz. Indeed, as that region is approached, Location 2 exhibits more acousti-

cal energy than Location 1. This can also be seen in Figure 8, where Location 1 exhibits a dip in the pressure levels starting at approximately 50 Hz, and that is not present in Location 2 (Figure 9). Similarly, the corresponding sonogram

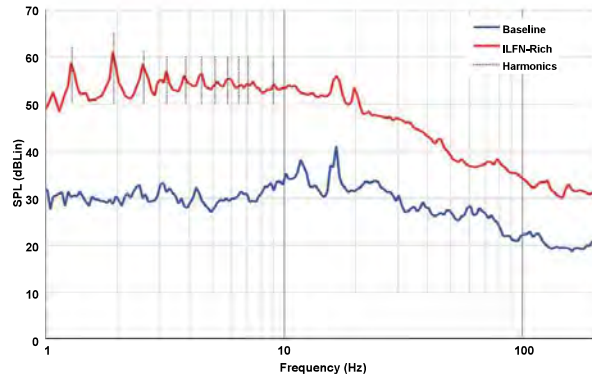


Figure 16: Narrow-band spectra comparing Location 1 - 14:40 on Dec 16 (Baseline) with Location 1 - 17:30 on Dec 30 (IL-FN-rich). Representative data over a 10-min interval and analyzed between 1-200 Hz.

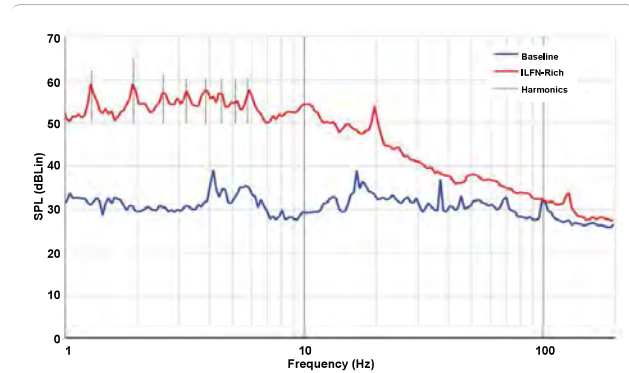


Figure 17: Narrow-band spectra comparing Location 2 - 15:50, on Dec 16 (Baseline) with Location 2 - 11:20, on Dec 30 (IL-FN-rich). Representative data over a 10-min interval and analyzed between 1-200 Hz.

Table 4: Data tables for 1/3-Octave-Band and dBA analyses. 1/3-Octave-Band Analysis of location 2 (New Shed), baseline, at 15:50, on Dec 16 (Figure 9).

Frequency (Hz)	SPL (dBLin)	SPL (dBA)
1.0	41.9	-106.7
1.3	41	-99.6
1.6	40.7	-91.9
2.0	39.1	-85.5
2.5	39.1	-77.6
3.2	39.1	-69.7
4.0	43.3	-57.5
5.0	42.8	-50.3
6.3	41.8	-43.6
7.9	37.4	-40.4
10.0	37.8	-32.6
12.6	40.3	-23.1
15.8	43.3	-13.3
20.0	42.6	-7.9
25.1	41.4	-3.4
31.6	40.2	0.8
39.8	40.9	6.2
50.1	40.5	10.2
63.1	40.2	14
79.4	38.1	15.6
100.0	38.6	19.5
125.9	36.2	20.1
158.5	35.5	22.2
199.5	36	25.1
251.2	38.4	29.8
316.2	41.7	35.1
398.1	43.8	38.9
501.2	41	37.8
631.0	38.8	36.9
794.3	39.4	38.5
Overall	55.3	44.9

Table 5: Data tables for 1/3-Octave-Band and dBA analyses. 1/3-Octave-Band Analysis of location 1 (Old Shed), baseline, at 14:40, on Dec 16 (Figure 8).

Frequency (Hz)	SPL (dBLin)	SPL (dBA)
1.0	39.9	-108.7
1.3	39.6	-101
1.6	38.7	-93.9
2.0	38.7	-85.9
2.5	39.9	-76.8
3.2	40.4	-68.4
4.0	38.8	-62.1
5.0	37.8	-55.2
6.3	39.2	-46.1
7.9	40.2	-37.6
10.0	42.9	-27.5
12.6	43.8	-19.6
15.8	44.7	-12
20.0	41.6	-8.9
25.1	41.7	-3
31.6	38	-1.4
39.8	36.6	2
50.1	35.6	5.4
63.1	36.2	10
79.4	33.5	11
100.0	31	11.9
125.9	29.8	13.7
158.5	28.4	15.1
199.5	28.6	17.8
251.2	29	20.4
316.2	33.7	27.1
398.1	38.6	33.8
501.2	37.4	34.1
631.0	30.8	28.9
794.3	29.5	28.7
Overall	53.6	38.6



(Figure 10) presents with several black areas in the >125 Hz region, while Location 2 has none (Figure 11). The fact that the total dBLin level is higher in Location 2 than in Location 1 (55.3 dBLin vs. 53.6 dBLin, Table 4 and Table 5, respectively), attests to the fact that more acoustical energy exists in Location 2 than in Location 1. This would seem to indicate that the elevated pressure levels occurring within the 10-25 Hz range in Location 1 (Figure 10, yellow areas) do not outweigh the evenly distributed pressure levels (> 125 Hz, in blue) shown in Location 2 (Figure 11).

ILFN-rich: In terms of 1/3-octave and dBA analyses, contrary to baseline, Location 1 now exhibits a higher total dBA level (53.4 dBA) (Figure 12 and Table 6) than Location 2 (44.9 dBA) (Figure 13 and Table 4), although the total dBLin values of both Locations are nearly identical (74.4 and 74.2 dB, Table 6 and Table 7, respectively).

Narrow-band-spectra methodology: Regarding the narrow-band spectra (Figure 16) a first peak can be seen at approximately 1.3 Hz with further peaks at 1.9, 2.6, 3.2, 3.8, 4.5, 5.2, 5.9 and 9 Hz. The blade passing frequency of an IWT consists of the number of times the blades rotate past the vertical tower structure, per second. Through video footage during the ILFN-rich measurements, that number was identified and the blade passing frequency was calculated as 0.65 Hz. These peaks correspond to a harmonic series with a fundamental frequency close to 0.65 Hz, and thus constitute an integral part of the IWT acoustical signature.

In Location 2, harmonics are not as prominent (Figure 17) as in Location 1, but peaks can still be seen at 1.3, 1.9, 2.6, 3.2, 3.9, 4.4, 5.2 and 5.9 Hz - again, acting as a signature of an IWT with a blade-pass frequency of about 0.65 Hz. An FFT of this frequency range (Figure 18) also shows these peaks.

Discussion

Large-scale public health epidemiological studies of residential ILFN contamination

Several exploratory studies have been conducted by governmental agencies [32-34] regarding the health effects of residential ILFN exposure. Many base their acoustical data on models (as per the dBA-1/3-octave methodology) rather than real, *in loco*, field measurements. Moreover, the unawareness of the importance of prior ILFN exposure histories when assessing health endpoints among study and control populations, predictably leads to statistically inconclusive results. As a consequence, many of the more classical groups of scientists who continue to defend the archaic notion “what you can’t hear won’t hurt you” feel justified in so doing. In the most recent French survey on the topic, results confirmed that: “wind turbines are sources of infra sounds and low-frequency sounds. However, the hearing

Table 6: Data tables for 1/3-Octave-Band and dBA analyses. 1/3-Octave-Band analysis of location 1 (Old Shed), ILFN-rich, at 17:30, on Dec 30 (Figure 12).

Frequency (Hz)	SPL (dBLin)	SPL (dBA)
1.0	59.4	-89.1
1.3	63.1	-77.4
1.6	60.8	-71.8
2.0	64.9	-59.7
2.5	64	-52.7
3.2	63.4	-45.4
4.0	63.5	-37.4
5.0	63.3	-29.8
6.3	63.3	-22.1
7.9	62.4	-15.4
10.0	62.5	-8
12.6	61.2	-2.1
15.8	62.3	5.6
20.0	59.8	9.3
25.1	56.6	11.9
31.6	55.4	15.9
39.8	52.5	17.9
50.1	48.8	18.6
63.1	46.2	20
79.4	46.2	23.7
100.0	43.3	24.2
125.9	41.6	25.5
158.5	40.7	27.3
199.5	45.1	34.2
251.2	49.8	41.2
316.2	49.1	42.5
398.1	50.7	45.9
501.2	49.2	46
631.0	49.9	48
794.3	46.8	46
Overall	74.4	53.4

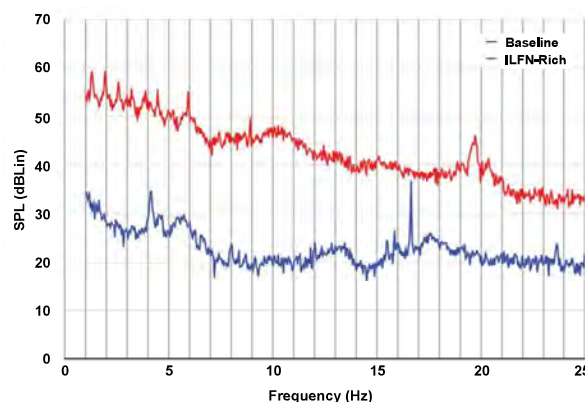


Figure 18: FFT power spectrum comparing Location 2 - 15:50, on Dec 16 (Baseline) with Location 2 - 11:20, on Dec 30 (ILFN-rich). Representative data over a 10-min interval and analyzed between 1-25 Hz.

thresholds for infra sounds and low frequencies of up to 50 Hz were not exceeded” [34]. Within the context of VAD studies, residential exposures have been investigat-



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ed using the same clinical endpoints as those that were found relevant for ILFN-exposed aeronautical technicians [20-22]. These document the accelerated onset of symptoms among families exposed to residential ILFN (generated by a grain terminal [21] and by IWTs [22]) when compared to occupational exposures.

Narrow-band analysis methodology vs. dBA methodology data for IWT-generated ILFN

The benefit of narrow-band analysis becomes obvious by the identification of discrete peaks in the presence of IWT rotation, and that are absent when IWT are not rotating (Figure 17 and Figure 18). These peaks have been identified as the harmonics of a fundamental frequency, whose value precisely coincides with that of the IWT blade-pass frequency (as verified by video footage). This type of information is impossible to obtain with the dBA-1/3-octave methodology.

As many acousticians would quickly point out, the increased acoustical energy in the shed caused by rotating IWT is indistinguishable from that caused by the wind (Figure 10 vs. Figure 14 and Figure 11 vs. Figure 15). Blowing wind outside will increase the acoustical energy in the ILFN range within practically any structure (whether or not it is heard by humans). Identifying specific acoustic signatures associated with IWT operation (as demonstrated in Figure 16, Figure 17 and Figure 18), can help pin-point the contributions made by the blowing wind (structure resonance), and differentiate those from anthropogenic ILFN. But this cannot be accomplished with the dBA-1/3-octave methodology, as shown in Figure 8, Figure 9, Figure 12 and Figure 13.

Narrow-band analysis can also provide information that may in the future be relevant for dose-response values, and which the dBA-1/3-octave methodology cannot. For example, in the specific examples shown for the ILFN-rich locations (Figure 14 and Figure 15), Location 2 has similar acoustical energy at 20 Hz as Location 1. And yet, it is in Location 1 that the animal owner prefers to keep his breeding males. This may suggest that the frequencies that are more important for understanding the abnormal animal behavior (as reported by the owner) are not within the 20 Hz region.

Concomitant occupational and residential ILFN exposures in aerospace workers

In the summer of 2015, the home near the animal-sheds was abandoned by the family. IWTs had begun rotating in September 2013, and the ensuing health deterioration of family members demanded their removal. To this day, however, the property owner must return there everyday to care for the animals that are his livelihood. As in other ILFN-contaminated residences [35], this farmer's health

Table 7: Data tables for 1/3-Octave-Band and dBA analyses. 1/3-Octave-Band analysis of location 2 (New Shed), ILFN-rich, at 11:20, on Dec 30 (Figure 13).

Frequency (Hz)	SPL (dBLin)	SPL (dBA)
1.0	60.8	-87.8
1.3	63.9	-76.7
1.6	61.8	-70.8
2.0	64.7	-60
2.5	63.9	-52.8
3.2	64.3	-44.5
4.0	65	-35.8
5.0	63.6	-29.4
6.3	63.1	-22.3
7.9	60.8	-17
10.0	62.4	-8
12.6	59.4	-4
15.8	57.6	1
20.0	58.3	7.8
25.1	52.6	7.9
31.6	49.4	9.9
39.8	46.6	12
50.1	46.4	16.2
63.1	45.3	19.1
79.4	43.1	20.6
100.0	41.2	22.1
125.9	40.4	24.3
158.5	37.1	23.8
199.5	36.5	25.6
251.2	37.8	29.1
316.2	40.7	34.1
398.1	42.9	38.1
501.2	40.7	37.5
631.0	37.5	35.6
794.3	37.5	36.6
Overall	74.2	44.9

continues to deteriorate considerably, having most recently been diagnosed with Post-Traumatic Stress Disorder.

Aerospace workers who are exposed to occupational ILFN greatly benefit from the recovery periods encountered in their homes (presumably absent of anthropogenic ILFN) [16,19,36]. A growing segment of the world population, however, particularly from rural and suburban areas, has been confronted with ILFN-contamination in their homes. Some of these families include aerospace professionals (and other occupationally exposed ILFN workers), who are now exposed to ILFN both at work and at home.

The ongoing citizen-based research effort into ILFN-induced pathology to which these authors contribute [30] includes providing proper acoustical evaluations to participating citizens' properties, and also providing pertinent medical diagnostic tests, including the established VAD diagnostic tests [16,21,37]. Within this context, initial steps include obtaining personal and medical histories from each participating citizen. Histories are ob-



tained through one-on-one interviews that can last over 2 hours. Some of the citizens already interviewed include aerospace workers who are (or were) occupationally exposed to ILFN environments. Of these, some were already sleeping in ILFN-rich homes (due to anthropogenic sources), while others were expected to have sources of anthropogenic ILFN constructed near (< 3 km) their residential areas. Clinical information revealed in the interviews and corroborated by accompanying medical documentation, has been reiterating the association between symptom gravity and overall ILFN exposure.

People exposed to ILFN at work and at home see an acceleration of the onset of ILFN-induced pathology when compared to individuals who 'only' have ILFN exposure at work (assuming similar fetal, childhood and adolescent ILFN exposures). Individuals who are only exposed to ILFN-rich environments in the home see an accelerated onset of symptoms when compared to those who are only exposed to occupational ILFN-rich environments [20-22]. The reasons for this are twofold: on the one hand, when ILFN-exposed workers leave their place of employment, they undergo a biological respite from the agent of disease; on the other hand, ILFN-rich environments in the home are usually synonymous with sleeping in an anthropogenic ILFN-rich environment. Biological processes that only occur during sleep time are now occurring in the presence of an agent of disease [38].

Limitations of this study

When laboratorial studies are conducted using airborne acoustical phenomena, environmental parameters can be controlled with more or less ease. In real environments, however, an acoustic environment will not be homogeneous over any significant area or any significant time. Outdoors the environment may be reasonably homogeneous over tens of meters (apart from the interference effects from multiple sound sources creating 'heightened noise zones' possibly only a few meters across [39]). However, indoor environments can vary significantly over distances less than a meter. Furthermore, the acoustical differences between the two locations may have been due to time-wise changes between recording times.

Conclusions

This report highlights the difference in acoustical information gathered with two distinct methods of analysis: one sanctioned by current legislation and guidelines, and focused on protecting hearing impairment (dBA-1/3-octave methodology); the other, sanctioned by the bio-physical sciences and focused on protecting whole-body health (narrow-band methodology). The latter provides important information on the temporal and frequency profiles that are crucial for understanding how ILFN affects human health (considering both immediate and long-term effects).

The archaic notion of "what you can't hear won't hurt you" is reflected in the dBA-1/3-octave methodology, i.e., the hearing sensory pathway is the only one through which ILFN can adversely affect humans. This position is incompatible with the Scientific Method and with evidence-based medicine when quantifying a potential agent of disease, such as ILFN.

The clinical evolution of ILFN-induced pathology greatly depends on exposure-time patterns. Individuals, who work in ILFN-rich environments and simultaneously live in ILFN-rich homes, may see an accelerated onset of specific symptoms when compared with individuals who only live in the ILFN-rich home, with no prior or current history of occupational ILFN exposure. Therefore, the increasing number of ILFN-rich acoustic environments within rural residential dwellings poses a serious problem for ILFN-exposed aerospace workers, as their biological recovery periods (that occur when away from the ILFN-rich environment) may be greatly reduced, or even become non-existent.

In order to protect populations from excessive and harmful ILFN exposure, serious epidemiological studies under the auspices of 'Public Health' must be undertaken. An important step in that direction is taken here, showing the importance of departure from the established guidelines and legislation in order to obtain a scientifically useful quantification of the agent of disease under scrutiny.

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Due to his efforts in the creation of the SAM Scribe system, author HHCB has a financial interest in the SAM Scribe system.

Disclaimer

The authors of this paper:

- 1) Do not harbor anti-technology sentiments;
- 2) Consider industrial activities to be important to modern technological societies;
- 3) Have scrutinized the data under one and only on agenda - pure scientific inquiry;
- 4) Are not producing a report arguing against industrial complexes;
- 5) Are not producing an environmental noise assessment report focused on wind turbines;



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6) Provided all acoustical evaluations and analyses pro bono.

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Preliminary Field Report

Project: Independent Infrasonic Investigations
Location: Vicinity of Golden West Wind Facility, El Paso County, CO

Report Date: 29 January 2016

Investigator: Robert W. Rand, ASA, INCE
Rand Acoustics, Boulder, CO

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1.0 Summary

Differential acoustic pressure measurements were acquired and logged at three homes in the vicinity of the Golden West Wind Facility in El Paso County, Colorado during December 2015 and January 2016. A week of data was analyzed for each of the three homes and daily spectrograms produced which are attached. Each day's data consisted of approximately 4.3 million differential pressure samples with a week comprised of some 30.5 million samples.

Preliminary investigation confirmed the presence of recurring acoustic pressure oscillations at 0.2 to 0.85 Hz (the "blade pass frequency" or BPF) which are associated to the Golden West wind turbine rotations. At times multiple oscillation frequencies were observed, consistent with multiple turbines operating at different rotation rates. Oscillations appeared to be more pronounced when the turbines are more upwind rather than downwind. Neighbors reported they are mostly downwind due to turbine location relative to home location and for the prevailing winds in the region.

Typical BPF total acoustic power were computed for example portions of the differential pressure data sets. Crest factors (the ratio of RMS to peak levels) were also computed for segments dominated by wind turbine rotation and uncontaminated by other noise, with typical crest factors of 13-19 dB. Totalized BPF RMS levels ranged from 56 to 70 dB re 20uPA, with peak levels from 71 to 89 dB. The RMS and peak levels are similar to those found at other sites with appeals to stop the noise, legal action, and homes abandoned.

It is understood from neighbors that they have experienced disturbance since the turbines started operating whereas prior to turbine operation there was no similar disturbance. It is understood that neighbors report improvement when turbines are shut down (not rotating) or when they remove themselves physically away from the Facility a distance of several miles.

El Paso County noise regulations define "Sound" as oscillations in pressure (or other physical parameter) at any frequency, and, prohibits noise disturbance due to acoustic oscillations.

The analysis is far from complete in that numerous segments of each day at each monitoring location could be analyzed and associated to journal entries and/or medical data. The reported association of proximity to the operating facility to disturbance in health and quality of life appears supported by the acoustic data acquired for this preliminary investigation. These preliminary investigations suggest that there is a condition of noise disturbance due to very low frequency acoustic pressure oscillations in the vicinity of the Golden West Wind Facility when it is operating, with more severe impacts downwind.

2.0 Project Description

Investigations of possible infrasonic acoustic oscillations on properties were requested in 2015 by neighbors living in El Paso County in the vicinity of the newly constructed Golden West Wind Facility.

2.1 Methodology

Independent data acquisition for acoustic, sensation, and medical data. This report presents acoustical data primarily, with reference to neighbor journal reports. Medical data are not discussed in this report.

2.2 Acoustic data acquisition

- Sensors:** Infiltec INFRA-20 solid-state differential pressure sensor as micro barometer, +/-25Pa, 16-bit, serial data output at 9600 baud, 0.000945 Pascals per count, 50 Hz sample rate. High-pass pneumatic filter at 0.05 Hz and high pass digital filter at 0.125 Hz. Analog 8 Pole elliptic filter with 20 Hz corner frequency for anti-aliasing.
- Loggers:** Rand Acoustics SDL2 Serial Data Logger. Serial data stored hourly to SD card files with time synchronized to GPS.
- Calibration:** INFRA-20 micro barometers operate as differential (not absolute) pressure sensors with differential sensitivity calibrated at factory. Digital gain in INFRA-20 serial data output fixed at 0.000945 Pascals per count. Total pressure range, +/-25 Pascal.
- Setup:** Installation by INCE member or through trained instruction by INCE member on installation and operation of infrasonic sensor and data logger system in home. Sensor and logger set up in quiet location in home and run unattended. SD storage card changed at intervals as required.
- Analysis:** SpectraPlus SE time series, spectrogram and spectrum analysis. Imported INFRA-20 data Digitally resampled to 50 Hz using linear phase bandlimited interpolation algorithm combined with large oversampling, passband 0 to 22 Hz. Typical FFT frame used 8192 samples, Hanning weighting, 81.92 second FFT frame, no averaging, 50 percent overlap.

2.3 Sensation data acquisition

- Journals:** Journals kept by neighbors to document sensation and conditions.

2.4 Medical data acquisition

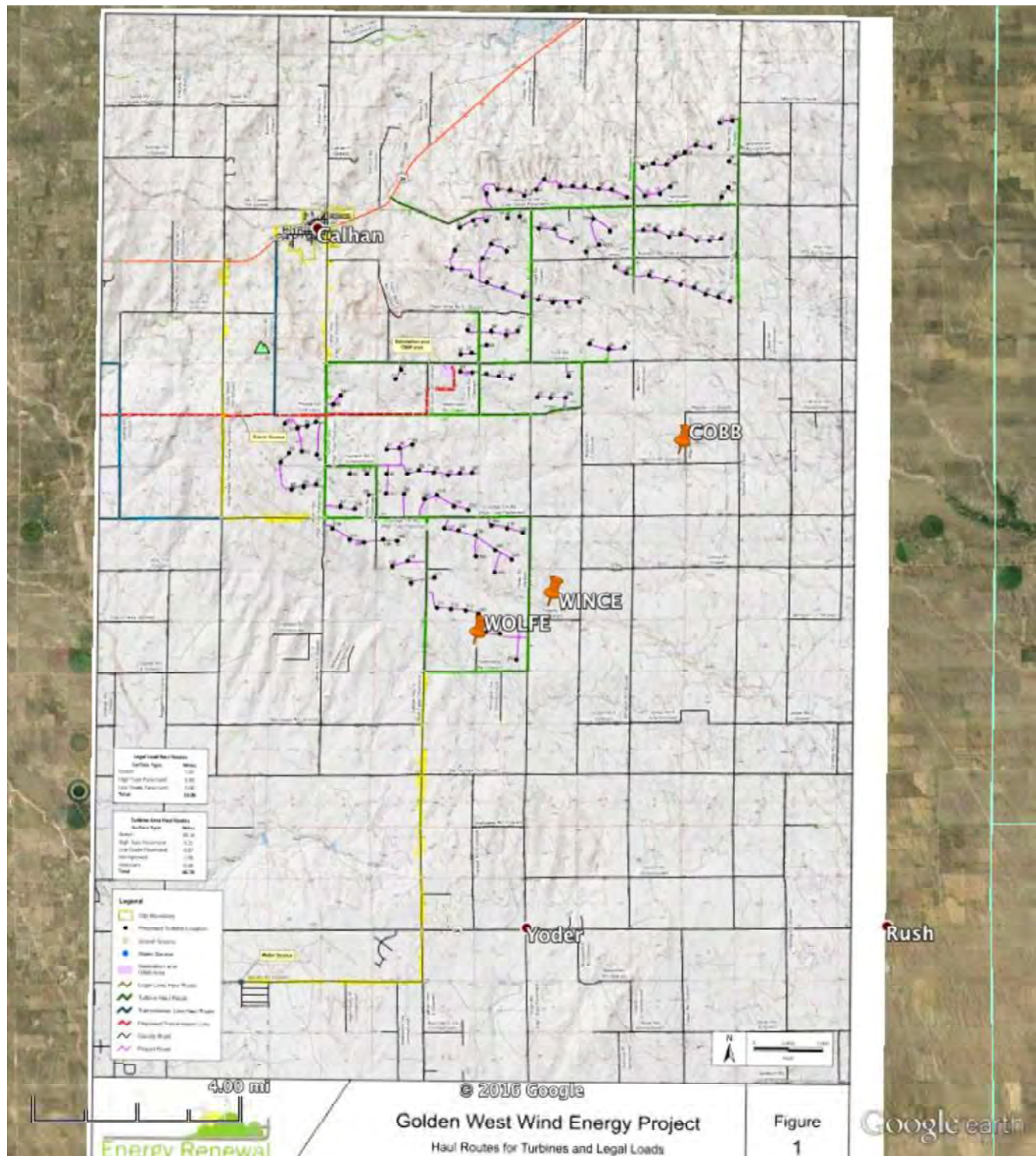
- Data:** Acquired by neighbors with medical supervision independent of acoustic data acquisition.

2.5 Survey bias description

None. Acoustic data collected blind from journal and medical data sets.

2.6 Project location and weather figures

Figure 1. Monitoring locations and Golden West Facility scaled in Google Earth.



Note: Data acquired inside homes at home locations marked COBB, WINCE, and WOLFE.

Figure 2. Detail map showing proximity of turbines to WOLFE and WINCE homes.

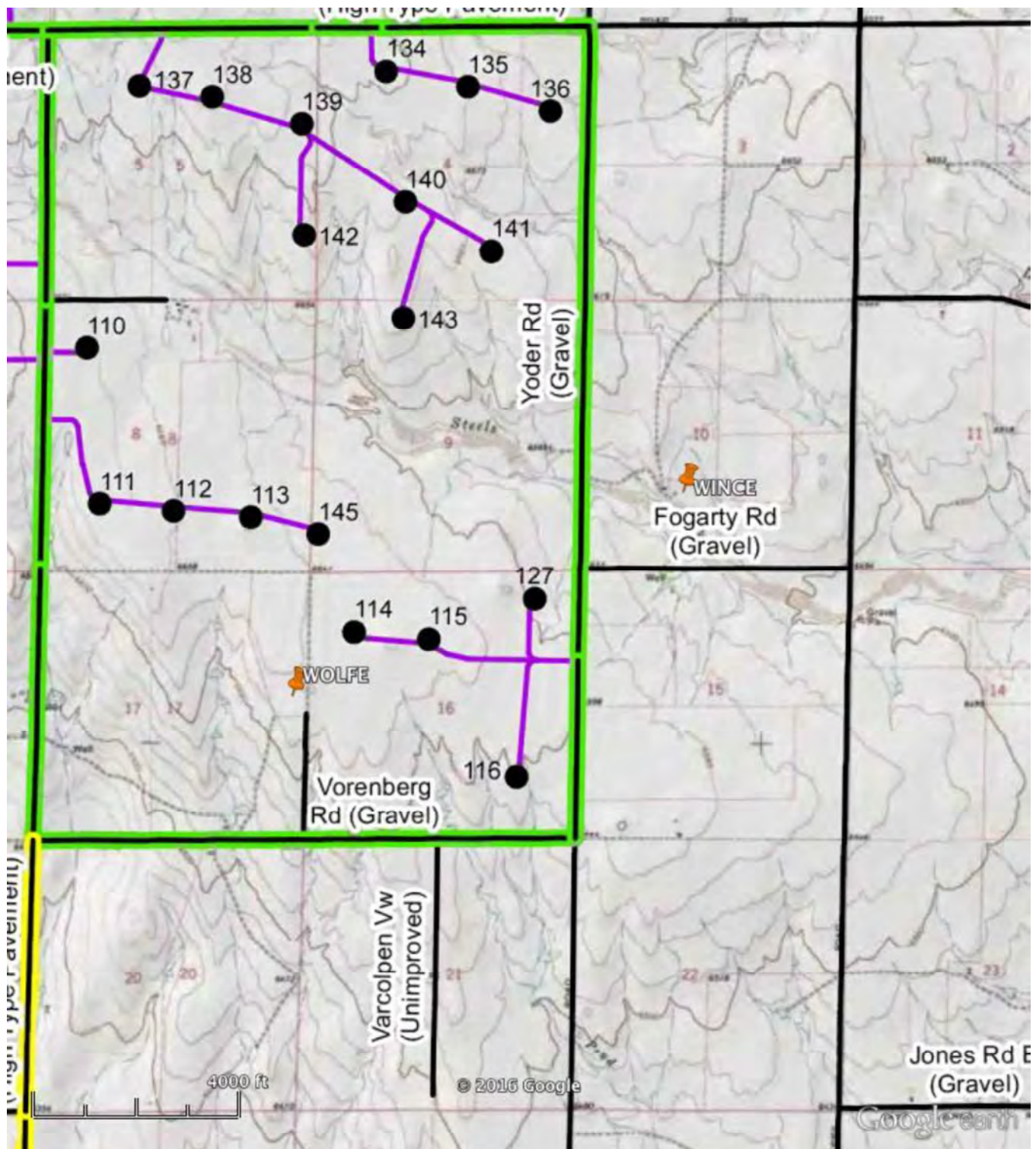


Figure 3. Weather December 11-17, 2015 (nearest airport, KFLY, Peyton, CO).

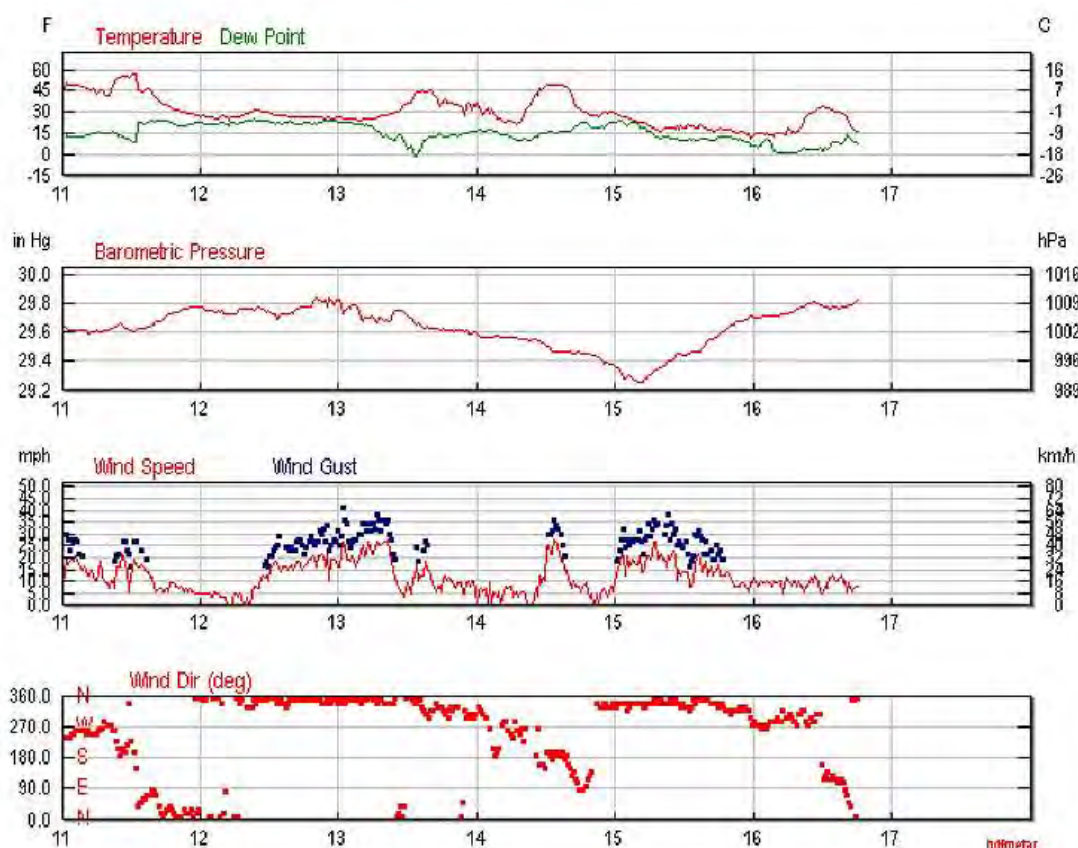
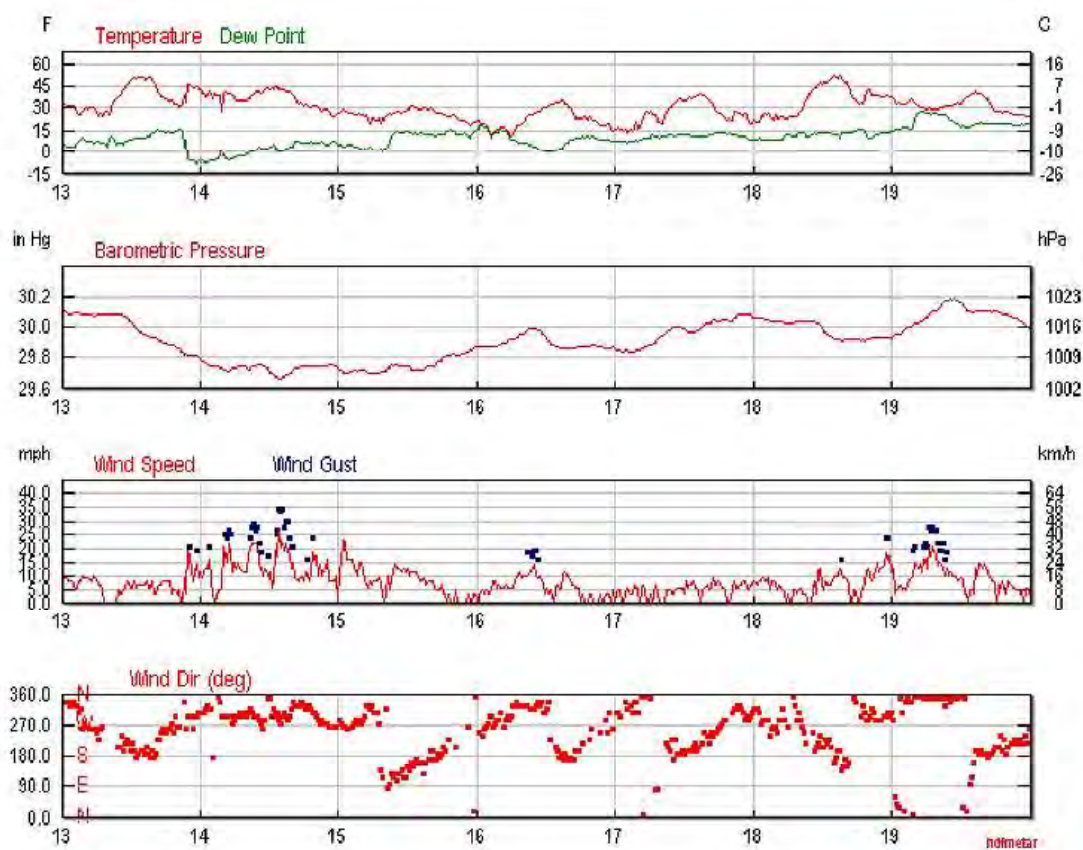


Figure 4. Weather, January 13-19, 2016 (nearest airport, KFLY, Peyton, CO).



3.0 Background Information

3.1 Applicable regulations

El Paso County has a noise regulation, Ordinance Number 02-1, adopted by the Board of County Commissioners on August 1, 2002, which prohibits noise disturbance. The law regulates acoustic pressure oscillations at any frequency including infrasonic (below 20 Hz). From Section 3:

(e) "Noise Disturbance" means any sound which is:

- (1) Harmful or injurious to the health, safety or welfare of any individual; or
- (2) Of such a volume, frequency and/or intensity that it unreasonably interferes with the quiet enjoyment of life of an individual of ordinary sensitivity and habits; or
- (3) Unreasonably interferes with the value of real property or any business conducted thereon.

and

(k) "Sound" means an oscillation in pressure, stress, particle displacement, particle velocity or other physical parameter, in a medium with internal forces. The description of sound may include any characteristic of such sound, including duration, intensity and frequency.

and

(m) "Sound Pressure" means the instantaneous difference between the actual pressure and the average or barometric pressure at a given point in space as produced by sound energy

and from Section 4:

SECTION 4. Prohibited Activities:

- (a.) It shall be unlawful to engage in any of the following activities, whether by use of a sound producing device, other device, or other means (either natural or artificial):
 1. To knowingly permit, make, cause to be made or continue any noise disturbance, as defined in Section 3(e) of this Ordinance.

The El Paso County law defines "Sound" as oscillations in pressure (or other physical parameter) at any frequency, and, prohibits noise disturbance due to acoustic oscillations. Large, three-bladed industrial wind turbines emit acoustic oscillations at the blade pass frequency (BPF), defined as:

$$\text{Blade pass frequency} = \text{Rotation rate, rpm} * 3 / 60, \text{ Hz}$$

A quick conversion is possible between BPF and rpm by using the multiplier or divider 20.

$$\text{BPF} = \text{rpm} / 20, \text{ Hz}; \quad \text{rpm} = \text{BPF} * 20, \text{ rotations per minute}$$

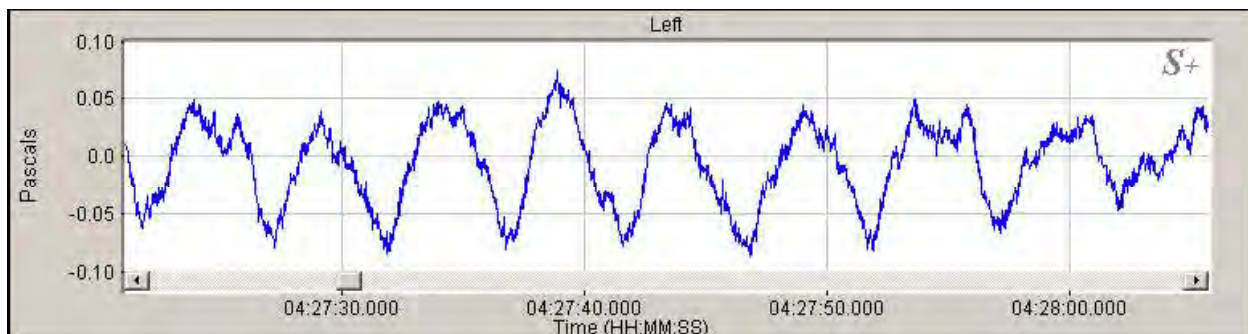
3.2 Acoustic pressure oscillations at infrasonic frequencies

Turbine specifications for the GE product line including the 1.7-100/103 and 1.715-100/103 list the rpm range of approximately 9.75 to 17.5 rpm (0.4875 to 0.875 Hz “blade pass frequency” or BPF) for power production.

There is a 0.2 BPF rate (4 rpm) understood to be associated with firmware- or operator-activated rotation by turbine turning gears to avoid bearing failure, requiring external power for the process.

Measurements during this preliminary investigation confirmed the presence of recurring quasi-impulsive pressure oscillations at 0.2 to 0.8 Hz at the monitoring locations in the vicinity of the Golden West Wind Facility. The presence of harmonics in FFT analysis suggests the pressure oscillations are pulse type waveforms with a narrowed duty cycle, rather than sinusoidal waveforms. This pulse type waveform is consistent with known attributes of wind turbine blade loading. From Malcolm Swinbanks: “The feature of impulsive noise is that there is a large signal present for a short period of time. Consequently, the mean, or root-mean-square (rms) level of the signal may be very low, apparently well below the threshold of hearing, but the peak level is much higher and can be perceived. This ratio of peak-to-mean level is the Crest-Factor.”¹

A time series chart is shown below illustrating the impulsive oscillation waveform at 0.2 Hz rotation, or a 5-second period at the Cobb home, 12-12-15 4:27 AM; winds light or absent at ground level, turbines apparently unpowered and turned by firmware at 4 rpm with internal turning gear using grid power.



The recurring yet non-repeating pulse waveform at the BPF is associated to the variable loading and release of each blade’s power accumulation as it swings through the fastest wind aloft and then down off top azimuth, and also, from interaction of each blade encountering the slowed-wind profile in the vertical bow wake upwind of the turbine tower.² It is understood that wind turbine firmware, relying on wind data from sensors at only one central elevation at the hub, is unable to keep blade angles optimized for each

¹ Malcolm Swinbanks, Re: Case No U-15899, to Executive Secretary, MPSC, 12-8-2009.

² Personal communications with Malcolm Swinbanks and Stephen E. Ambrose, INCE (Board Cert.).

blade along its length as the blades swing through hundreds of feet variations in wind speed, vertical and veer shear and turbulence often exceeding manufacturer operating specifications.

Dynamic stall, excessive blade moments (range of motion) and excessive bearing loads have been documented by turbine performance research for wind turbines operated in environments with wind conditions exceeding manufacturer operating specifications. Acoustically, it appears that blade unloading and dynamic stall result in blades swinging flapwise like large paddles or long speakers, amplifying blade moments and recurring pulsatile oscillations at the blade pass frequency. Sudden encounters with changes in wind speed or direction may shock blades into ringing at their primary structural resonant frequencies which are also infrasonic.

It is understood that it is possible to rotate turbines at up to full rpm with no power output using feathered blades (no angle to wind) and externally applied voltage to internal gearing. In such operations, the blades would still be subjected to wind shear and turbulence and exhibit cyclical flapwise moments resulting in acoustic oscillations at the blade pass frequencies.

3.3 Motion sickness from oscillations

International ISO standard 9996:2000 defines motion sickness from exposure to actual or perceived oscillatory motion; *“motion sickness is a commonly experienced and sometimes severe but reversible (i. e. physiological) disorder specifically associated with exposure to actual or perceived oscillatory motion in the frequency range 0,1 to 1 Hz. One or more of a constellation of symptoms (with or without frank vomiting) may affect the sufferer. ”*

Naval studies identified acceleration oscillations in the range of 0.1 to 1 Hz as associated with motion sickness, with sickness strongest at about 0.2 Hz. The association of acoustic oscillations to motion sickness was documented in studies of large wind turbine noise emissions by Dr. Paul Schomer.

Review of deliberate increases in wind turbine size over several decades indicates that the rotational rate (revolutions per minute or rpm) and the blade pass frequency (BPF) have dropped, as size increased, into the range of motion sickness identified in ISO 9996:2000, 0.1 to 1 Hz and studied in naval research on motion sickness. Figure 5 below illustrates the drop in BPF with turbine size. Blade pass frequencies observed in spectrogram analysis at homes near the vicinity of the Golden West Wind Facility fall within 0.2 to 0.85 Hz, within the range associated to motion sickness.

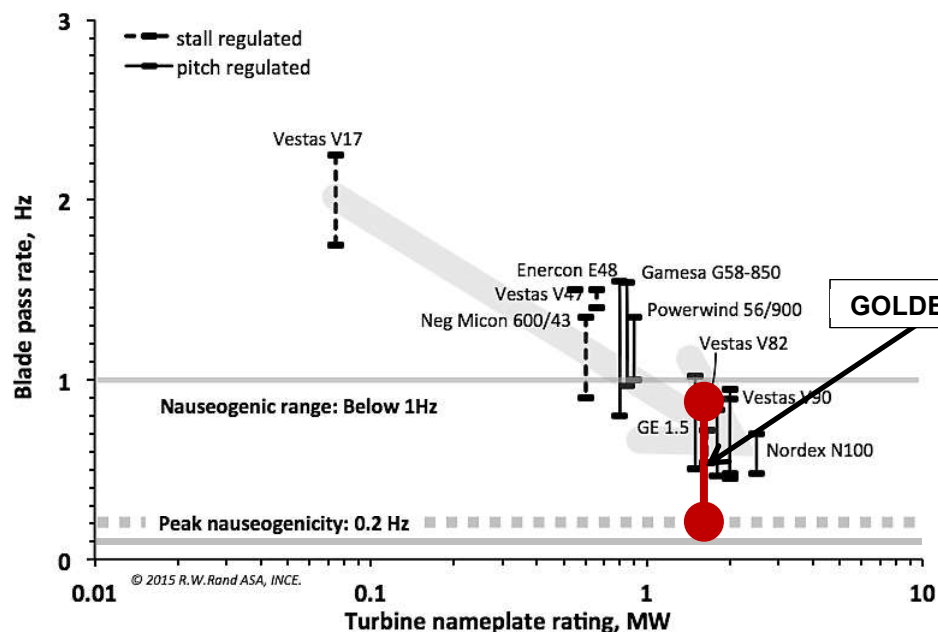
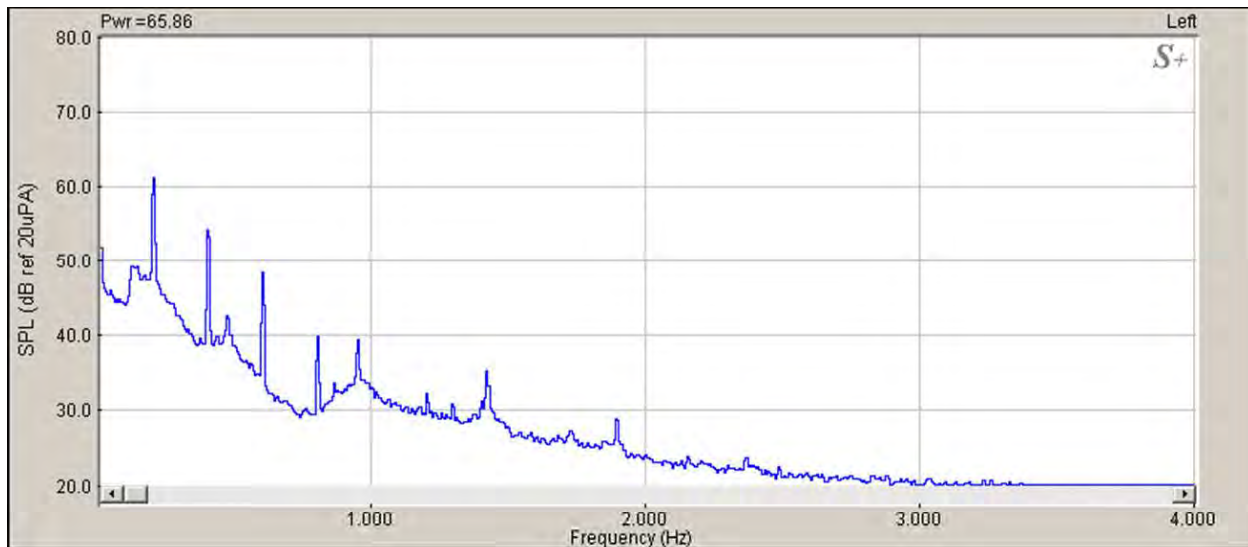


Figure 5. Blade pass rate (frequency), Hz for various wind turbine models. Nauseogenicity range is 0.1 to 1 Hz with peak nausea potential noted at 0.2 Hz. In a limited literature search, motion sickness reports were not found for older, smaller turbines, which have blade pass frequencies outside the nauseogenic range. This figure includes minor syntax changes from a figure presented at the 4pNS Wind Turbine Noise II technical at the 2015 Acoustical Society of America Meeting in Pittsburgh.

4.0 Spectrum analysis of BPF oscillations

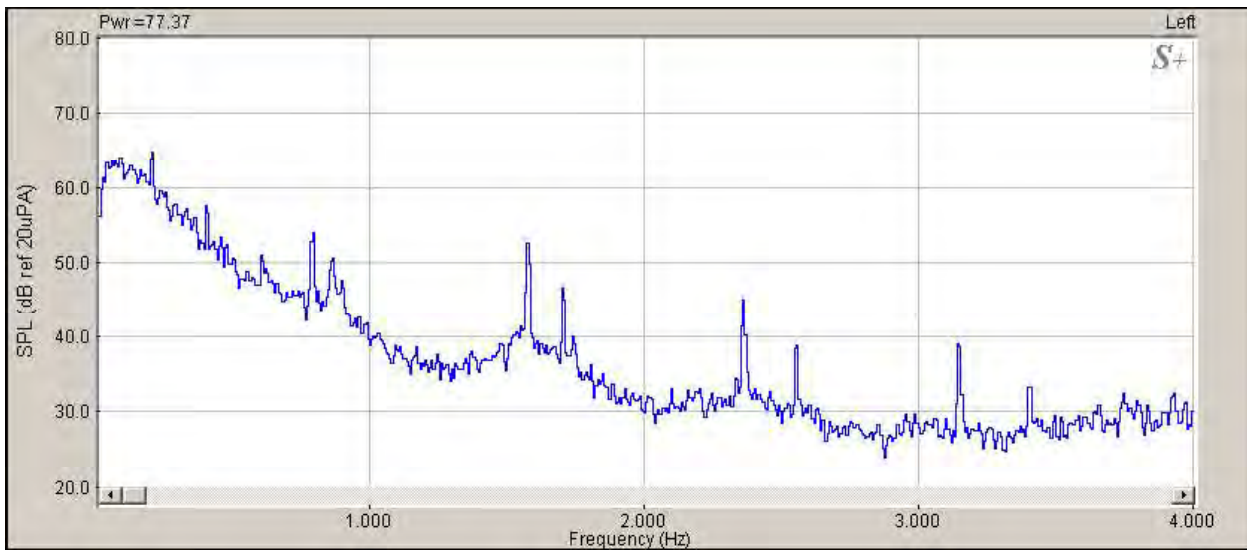
Power levels were computed for several monitoring segments by summing the first four FFT components for specific turbine rotations when the traces were clearly visible and uncontaminated by other noise. For a 0.2 Hz rotation, the FFT power for 0.2, 0.4, 0.6, and 0.8 Hz were summed using the center and two adjacent bins for each harmonic. Similar summations were performed for other rotations such as 0.85 Hz. Totalized RMS levels ranged from 56 to 70 dB re 20uPA, with peak levels from 71 to 89 dB. Crest-Factors were obtained directly in analysis software and applied to obtain the peak BPF sound level.

4.1 Example 1. Spectrum analysis, Cobb Home, 12-12-15, BPF 0.2 Hz.



DATE 12/12/15
 START TIME 1:15 AM
 STOP TIME 6:15 AM
 DURATION 5.00 hours

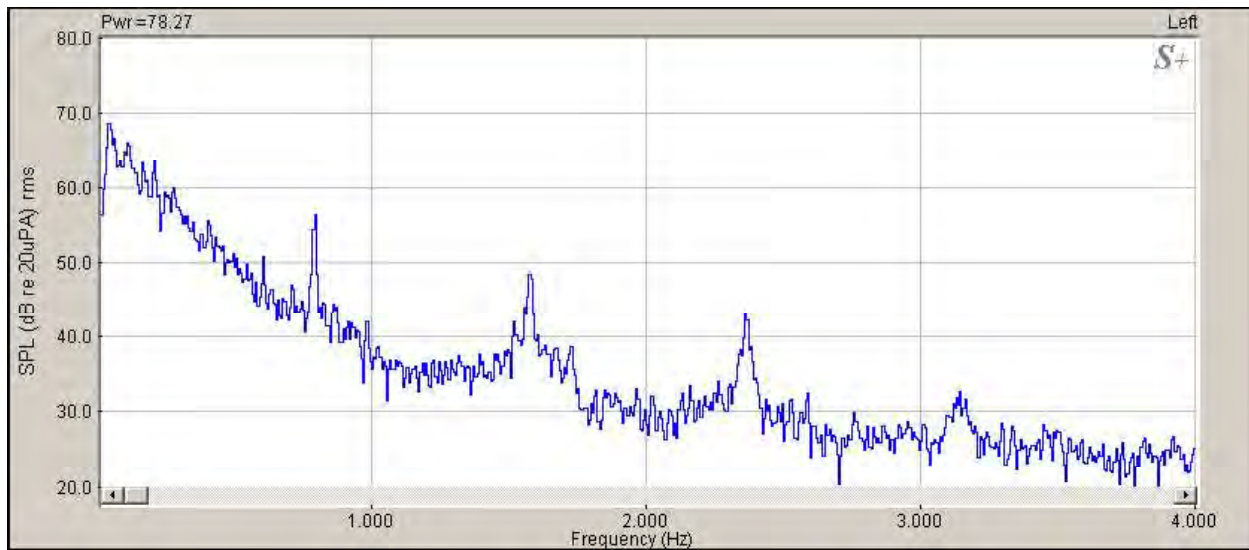
CALC OSCILLATION PWR	F, Hz	Bin, dB	Exp
BPF BIN-1	0.1953	59.2	825266.7
BPF BIN-1	0.2014	61.4	1389442.6
BPF BIN+1	0.2075	52.6	180170.1
2XBPF BIN-1	0.3906	43.7	23223.5
2XBPF	0.3967	54.4	277437.8
2XBPF+1	0.4028	53.4	218142.3
3XBPF BIN-1	0.592	41.9	15379.6
3XBPF	0.5981	48.6	72548.8
3XBPF+1	0.6042	44.3	27018.8
4XBPF BIN-1	0.7935	36.9	4918.4
4XBPF	0.7996	40.1	10188.8
4XBPF+1	0.8057	33.9	2476.3
TOTAL, dB re 20uPA			64.8
TOTAL, Pascals, RMS			0.035
CREST FACTOR, dB			17.6
Peak level, dB			82.4

4.1 Example 2. Spectrum analysis, Cobb Home, 12-13-15, BPF 0.2, 0.79, and 0.85 Hz.

DATE 12/13/15
 START TIME 6:15 PM
 STOP TIME 6:45 PM
 DURATION 0.50 hours

CALC OSCILLATION PWR	0.2 HZ			0.78 Hz			0.85 Hz		
	F, Hz	Bin, dB	Exp	F, Hz	Bin, dB	Exp	F, Hz	Bin, dB	Exp
BPF BIN-1	0.1953	63.9	2480279.9	0.7751	46.7	46247.0	0.8484	49.1	81903.8
BPF BIN-1	0.2014	65.0	3152360.7	0.7813	53.0	200254.0	0.8545	50.5	110926.0
BPF BIN+1	0.2075	60.4	1087195.1	0.7874	54.3	268226.1	0.8606	50.8	119487.3
2XBPF BIN-1	0.3967	57.8	602700.8	1.5625	46.3	42769.7	1.6907	39.4	8760.2
2XBPF	0.4028	56.7	467546.3	1.5686	52.7	187047.7	1.6968	46.8	48367.2
2XBPF+1	0.4089	52.0	159569.0	1.5747	50.0	100755.2	1.7029	45.2	33395.9
3XBPF BIN-1	0.5981	51.1	129169.2	2.3499	41.7	14642.2	2.5452	38.7	7441.6
3XBPF	0.6042	50.4	110293.4	2.356	45.2	33433.1	2.5513	39.1	8039.7
3XBPF+1	0.6104	48.7	74723.3	2.3621	40.5	11095.5	2.5574	31.8	1513.1
4XBPF BIN-1	0.7996	45.0	31683.0	3.1372	39.3	8498.8	3.3936	33.4	2207.1
4XBPF	0.8057	46.4	43980.1	3.1433	38.8	7545.5	3.3997	33.5	2244.0
4XBPF+1	0.8118	44.8	30323.4	3.1494	32.4	1752.2	3.4058	28.9	784.3
TOTAL, dB re 20uPA			69.2			59.6			56.3
TOTAL, Pascals, RMS			0.058			0.019			0.013
CREST FACTOR, dB			14.3			14.3			14.3
Peak level, dB			83.5			73.9			70.6

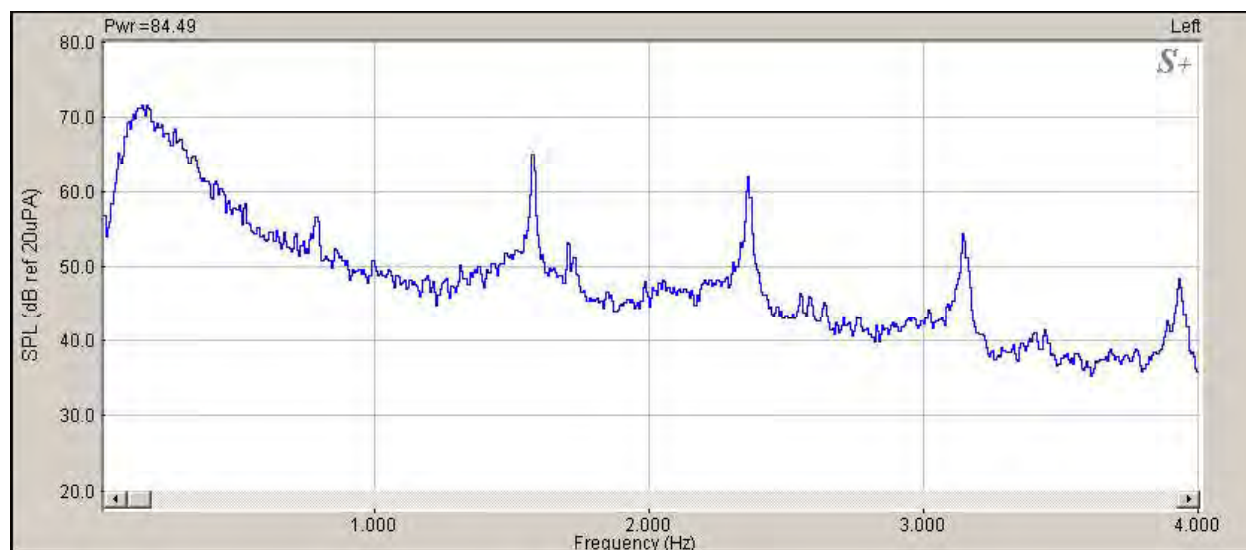
4.1 Example 3. Spectrum analysis, Cobb Home, 12-17-15, BPF 0.78 Hz.



DATE 12/17/15
START TIME 8:10 PM
STOP TIME 8:25 PM
DURATION 0.25 hours

CALC OSCILLATION PWR	F, Hz	Bin, dB	Exp
BPF BIN-1	0.7751	48.5	71339.8
BPF BIN-1	0.7813	54.6	289792.5
BPF BIN+1	0.7874	56.5	448172.3
2XBPF BIN-1	1.5625	45.6	36015.8
2XBPF	1.5686	48.6	72421.4
2XBPF+1	1.5747	48.0	62543.8
3XBPF BIN-1	2.3499	40.0	10082.5
3XBPF	2.356	43.2	20918.2
3XBPF+1	2.3621	42.4	17341.4
4XBPF BIN-1	3.1311	31.0	1258.4
4XBPF	3.1372	32.9	1967.6
4XBPF+1	3.1433	29.6	905.8
TOTAL, dB re 20uPA			60.1
TOTAL, Pascals, RMS			0.020
CREST FACTOR, dB			13.1
Peak level, dB			73.2

4.1 Example 4. Spectrum analysis, Wolfe home, 12-17-15, BPF 0.78 Hz.



DATE 12/17/15
START TIME 10:40 PM
STOP TIME 11:40 PM
DURATION 1.00 hours

CALC OSCILLATION PWR	F, Hz	Bin, dB	Exp
BPF BIN-1	0.7751	55.6	367190.8
BPF BIN-1	0.7813	56.8	478888.6
BPF BIN+1	0.7874	56.1	411701.8
2XBPF BIN-1	1.5625	59.8	954050.8
2XBPF	1.5686	65.1	3225940.1
2XBPF+1	1.5747	63.0	1975497.1
3XBPF BIN-1	2.3499	60.1	1020352.4
3XBPF	2.356	62.1	1635316.1
3XBPF+1	2.3621	59.3	846885.7
4XBPF BIN-1	3.1311	51.9	155949.2
4XBPF	3.1372	54.6	291209.0
4XBPF+1	3.1433	53.7	231877.6
TOTAL, dB re 20uPA			70.6
TOTAL, Pascals, RMS			0.068
CREST FACTOR, dB			18.2
Peak level, dB			88.8

4.1 Example 5. Spectrum analysis, Wince home, 1-19-16, BPF 0.78 Hz.



DATE 12/17/15
START TIME 6:00 PM
STOP TIME 11:00 PM
DURATION 5.00 hours

CALC OSCILLATION PWR	F, Hz	Bin, dB	Exp
BPF BIN-1	0.7751	48.5	70428.0
BPF BIN-1	0.7813	49.7	93111.6
BPF BIN+1	0.7874	50.0	100601.3
2XBPF BIN-1	1.5625	44.9	30595.2
2XBPF	1.5686	49.1	80677.5
2XBPF+1	1.5747	47.2	52168.2
3XBPF BIN-1	2.3499	42.3	16845.2
3XBPF	2.356	43.9	24320.6
3XBPF+1	2.3621	40.4	10961.0
4XBPF BIN-1	3.1311	35.1	3223.1
4XBPF	3.1372	38.7	7435.5
4XBPF+1	3.1433	38.0	6360.2
TOTAL, dB re 20uPA			57.0
TOTAL, Pascals, RMS			0.014
CREST FACTOR, dB			17.3
Peak level, dB			74.3

5.0 Infrasonic spectrograms

Daily spectrograms are shown in this section for the three homes monitored:

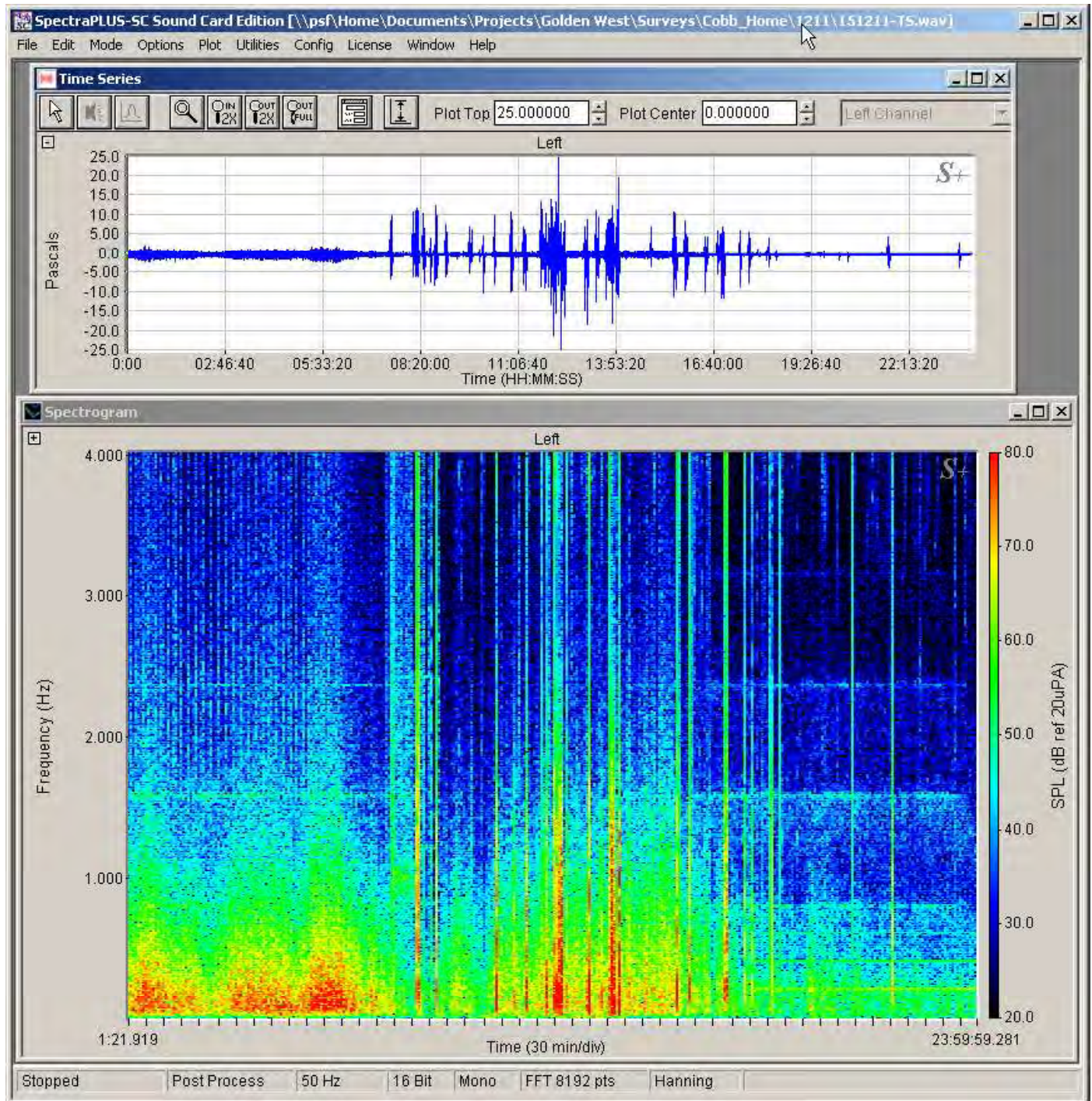
Cobb home: December 11-17, 2015

Wolfe home: December 11-17, 2015

Wince home: January 13-19, 2016

Location: COBB HOME

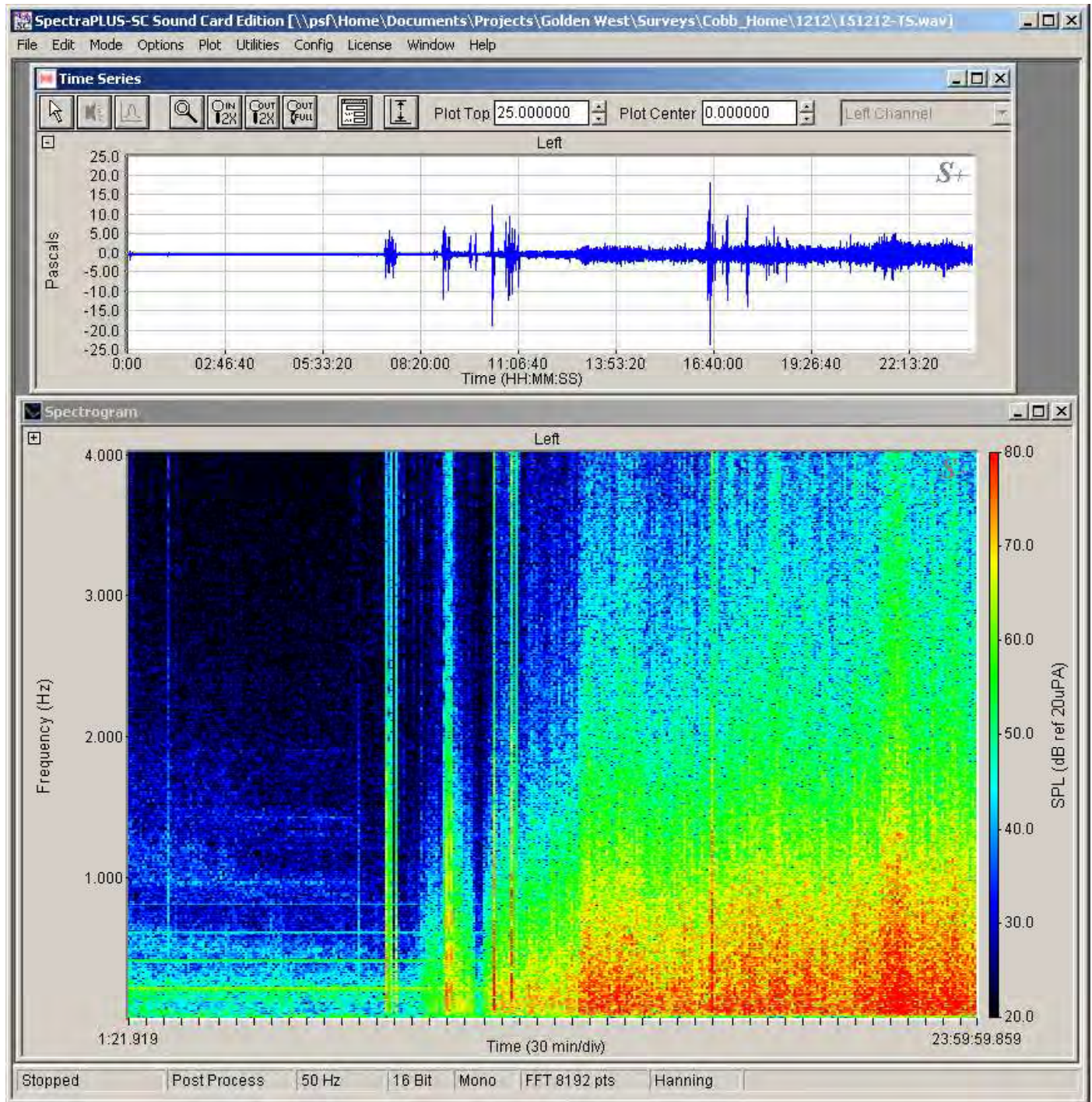
Date: 12/11/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations at 0.79 Hz (15.8 rpm) and 0.2 Hz (4 rpm) was observed. Multiple rotations in the range of 0.6 to 0.7 Hz were observed consistent with differing rotation rates from a number of turbines at some distance or at lower power.

Location: COBB HOME

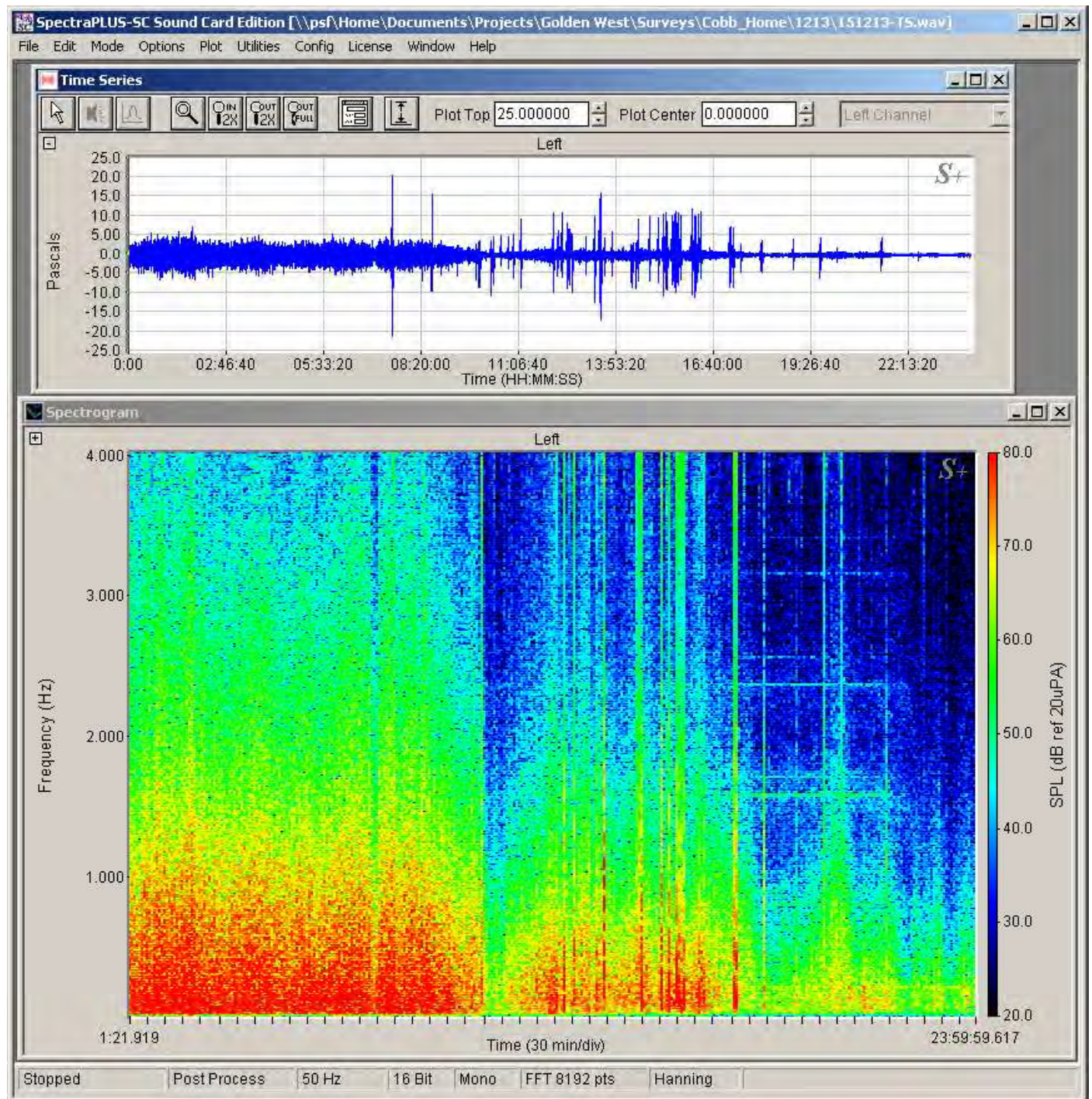
Date: 12/12/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations at 0.2 Hz (4 rpm) and 0.48 Hz (9.6 rpm) were observed. Multiple lower intensity traces in the range of 0.4 to 0.7 Hz were observed consistent with differing rotation rates from a number of turbines at some distance or at lower power. Slowing of multiple turbines from night before was observed to continue through to about 6:30 AM.

Location: COBB HOME

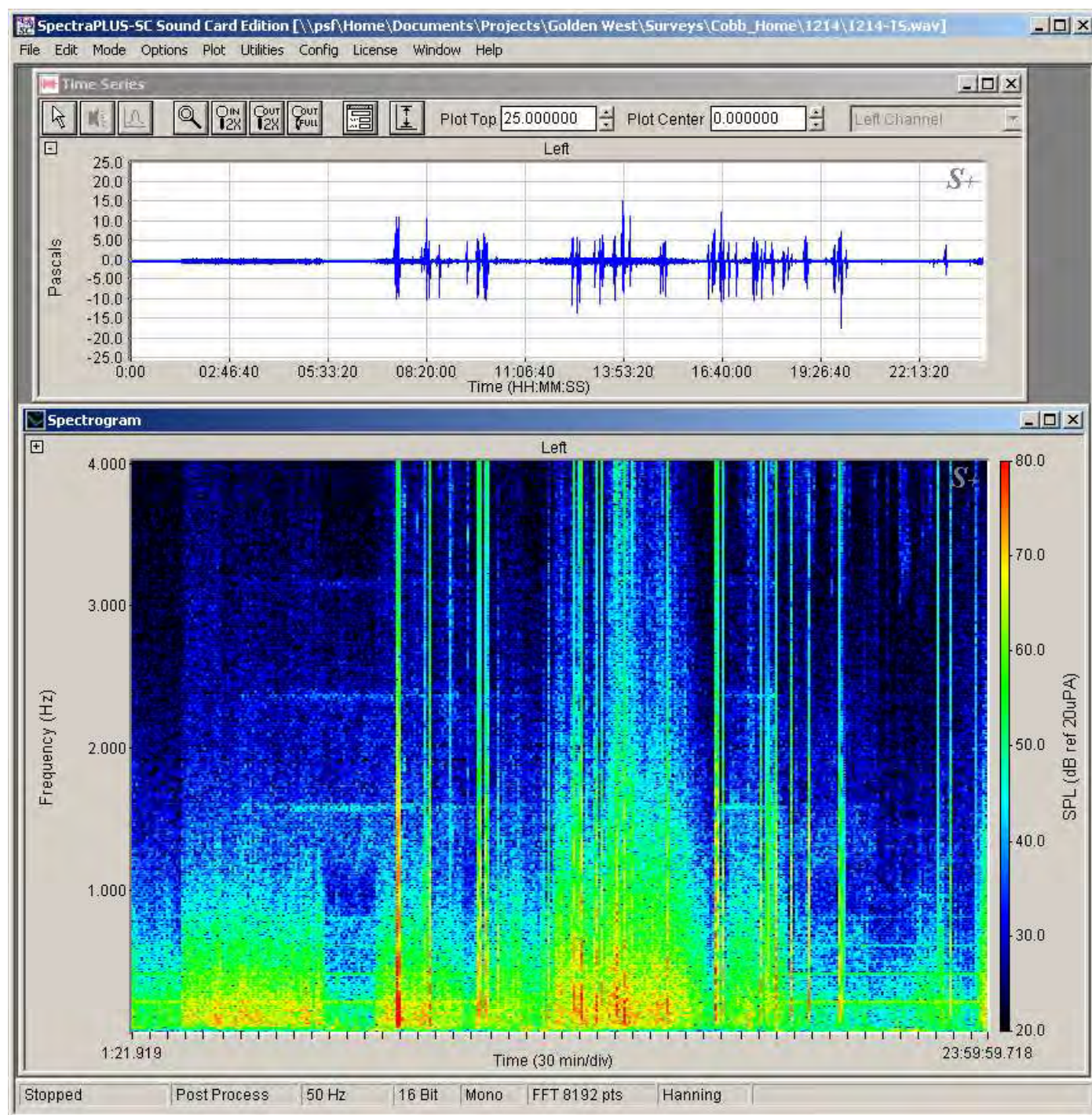
Date: 12/13/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations at 0.2 Hz (4 rpm), 0.79 Hz (15.8 rpm) and 0.85 Hz (19 rpm) were observed during the evening hours.

Location: COBB HOME

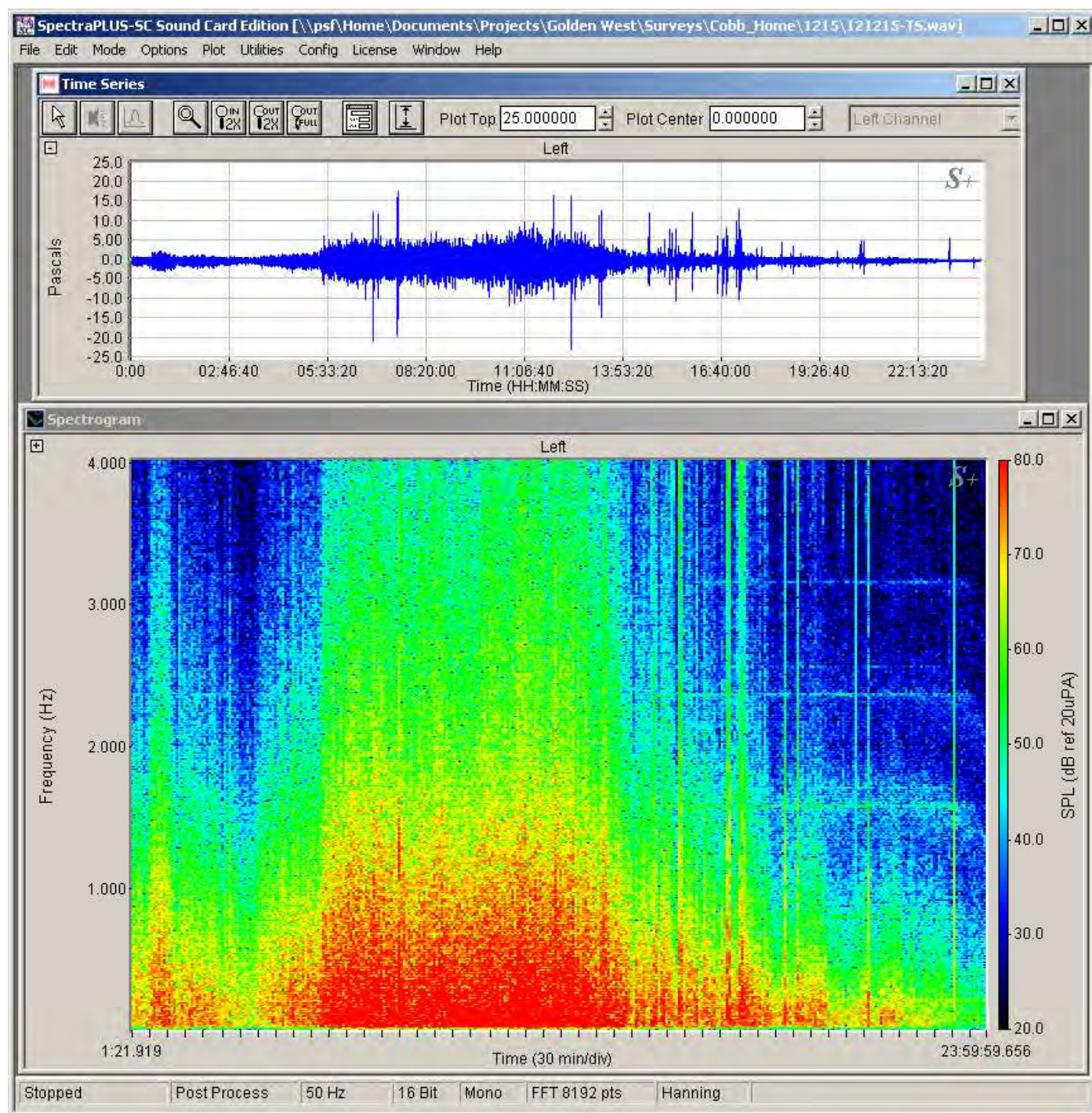
Date: 12/14/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations at 0.79 Hz (15.8 rpm) and 0.2 Hz (4 rpm) were observed.

Location: COBB HOME

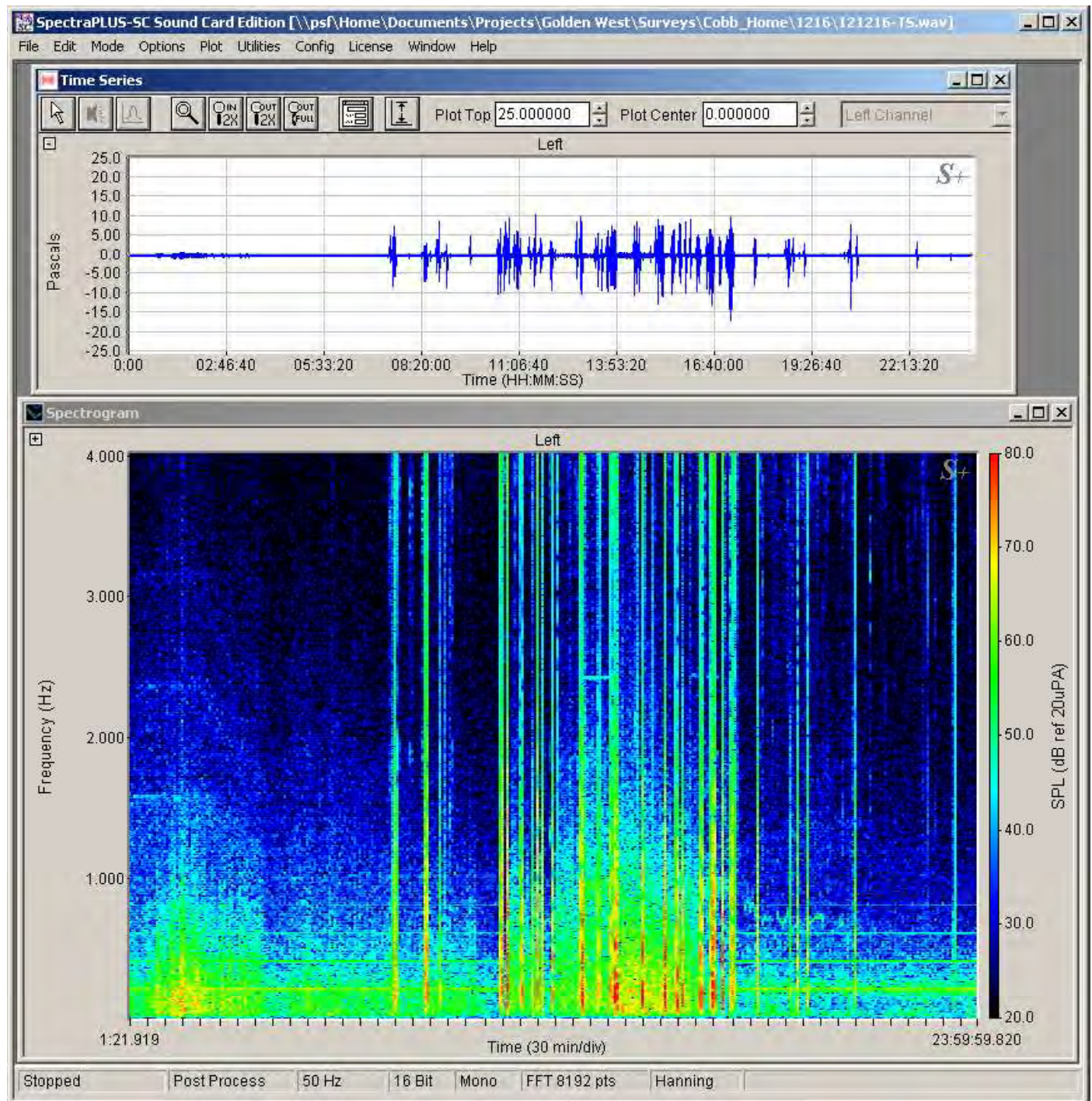
Date: 12/15/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations at 0.79 Hz (15.8 rpm) and 0.86 Hz (17.2 rpm) were observed.

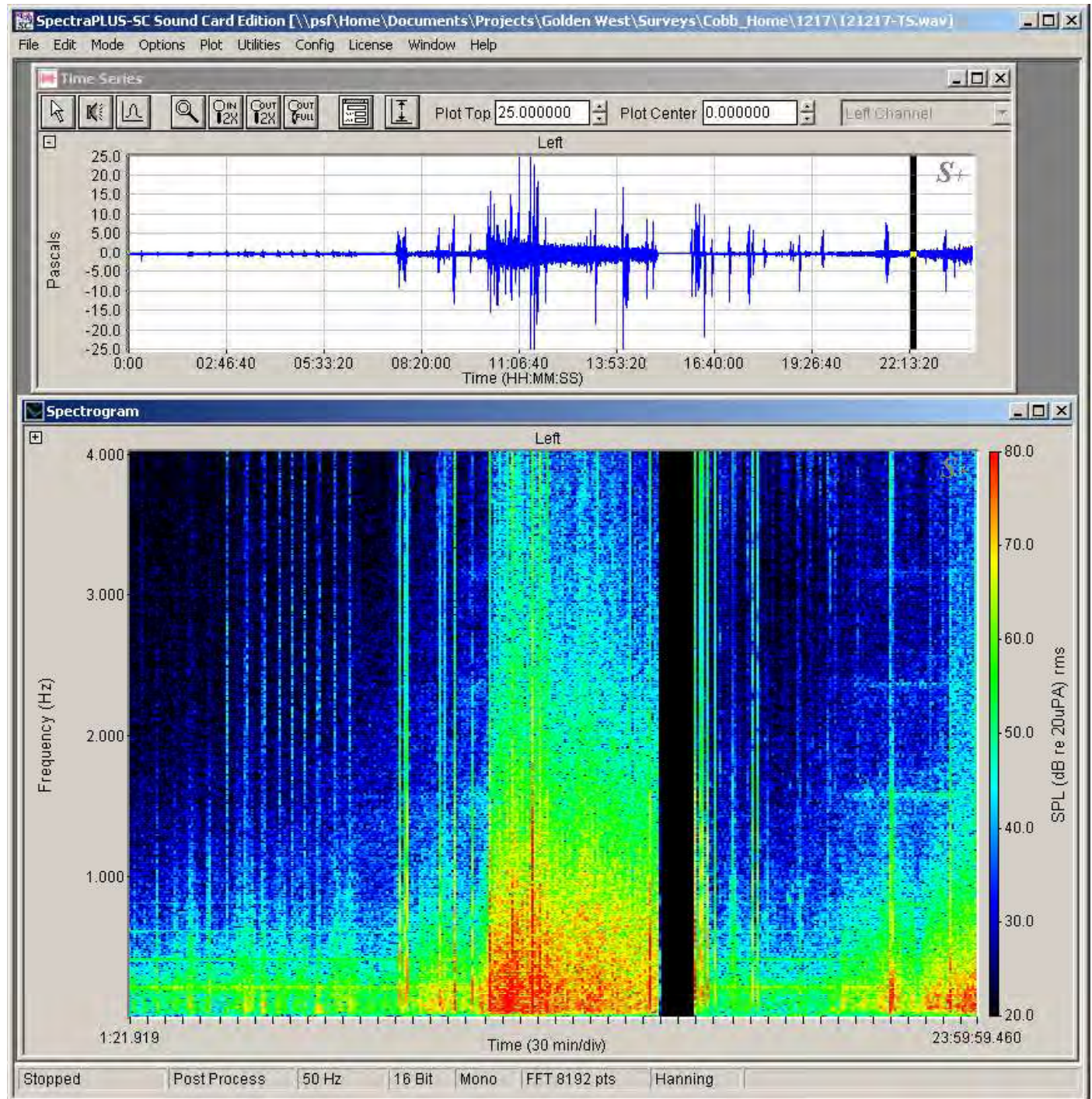
Location: COBB HOME

Date: 12/16/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations at 0.79 Hz (15.8 rpm) were observed until about 2:30 AM and 0.2 Hz (4 rpm) was observed the remainder of the day.

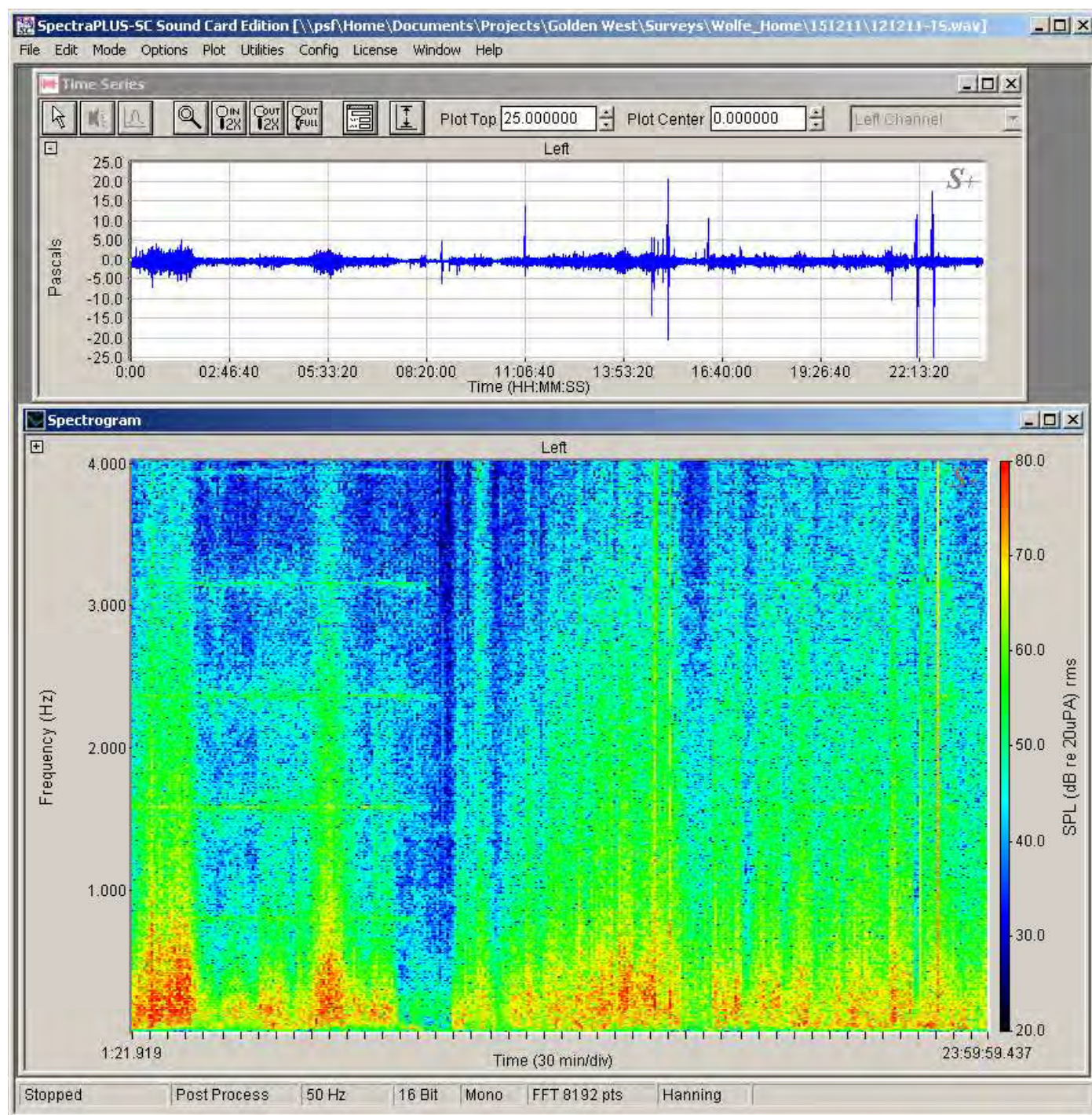
Location: COBB HOME
Date: 12/17/2015



Note: Horizontal traces indicate wind turbine rotation. Rotation at 0.2 Hz (4 rpm) during the first part of the day, with 0.79 Hz (15.8 rpm) rotations observed starting about daybreak, not visible in the mid-afternoon, and reappearing around 8 PM. Gap 3-4 PM for system maintenance.

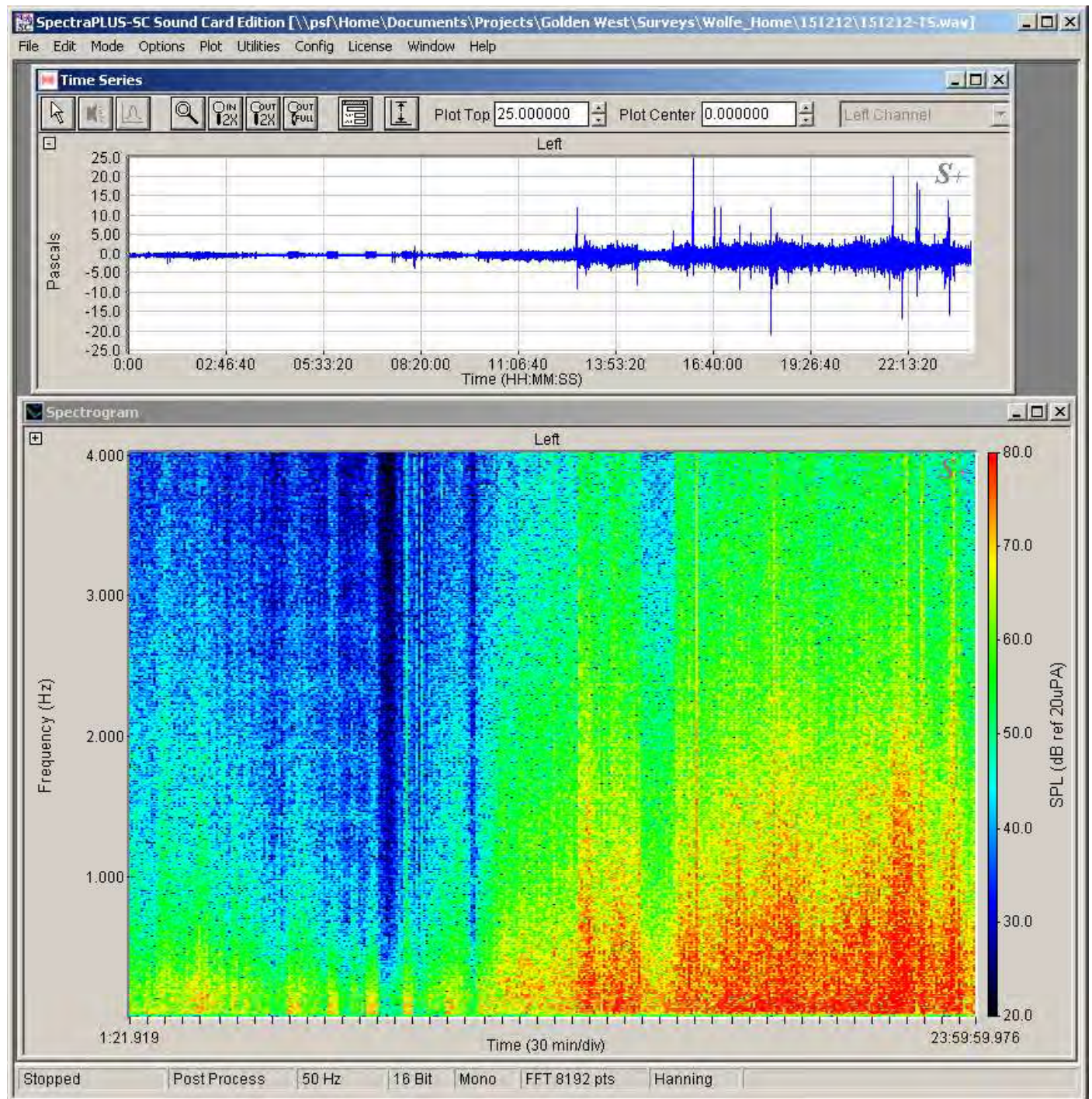
Location: WOLFE HOME

Date: 12/11/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations at 0.79 Hz (15.8 rpm) and 0.48 Hz (9.6 rpm) were observed.

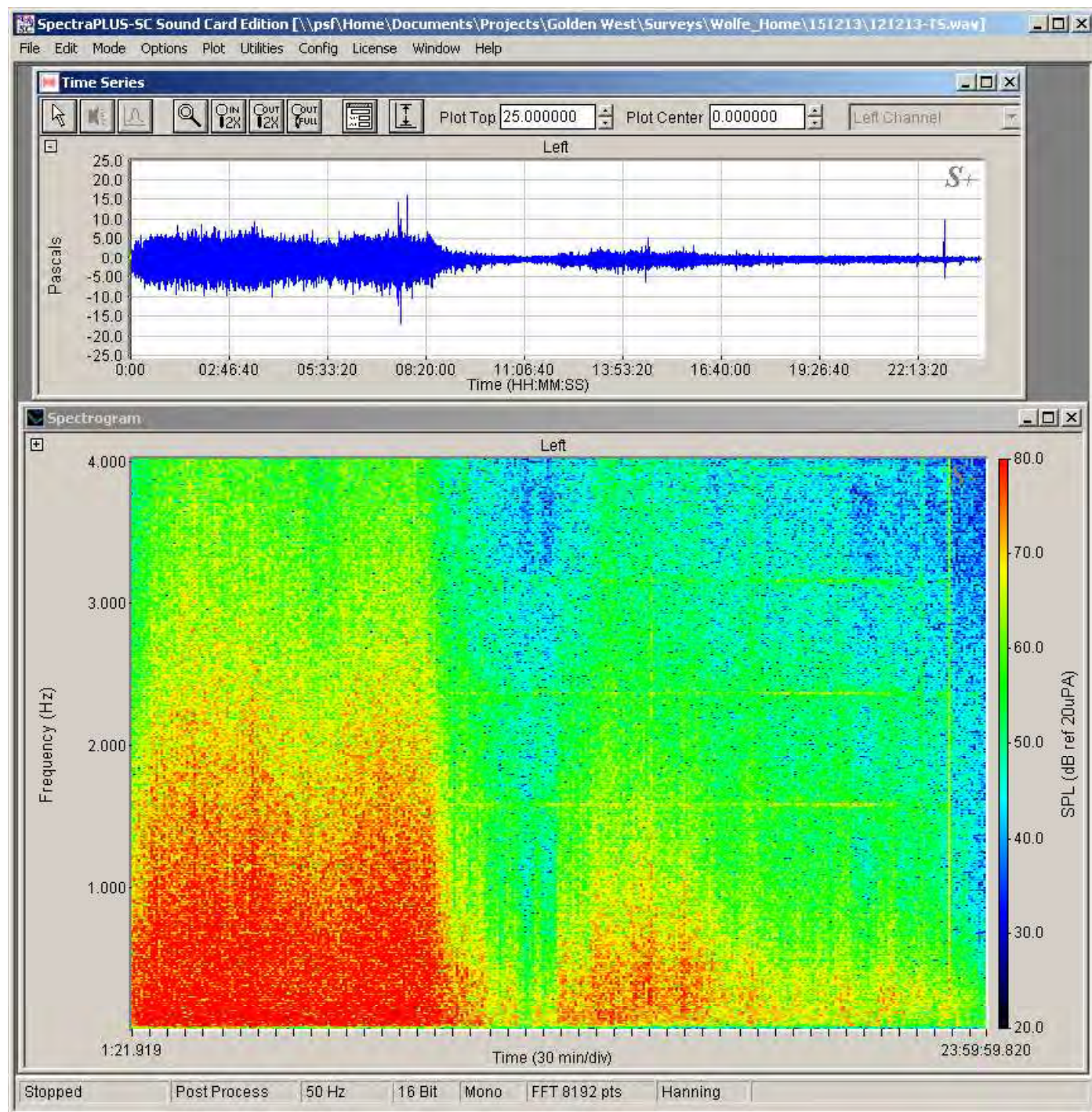
Location: WOLFE HOME
Date: 12/12/2015



Note: Horizontal traces indicate wind turbine rotation. Rotations were observed at 0.47 Hz (15.4 rpm) during early hours until 7 AM and 0.79 Hz (15.8 rpm) after 12 PM.

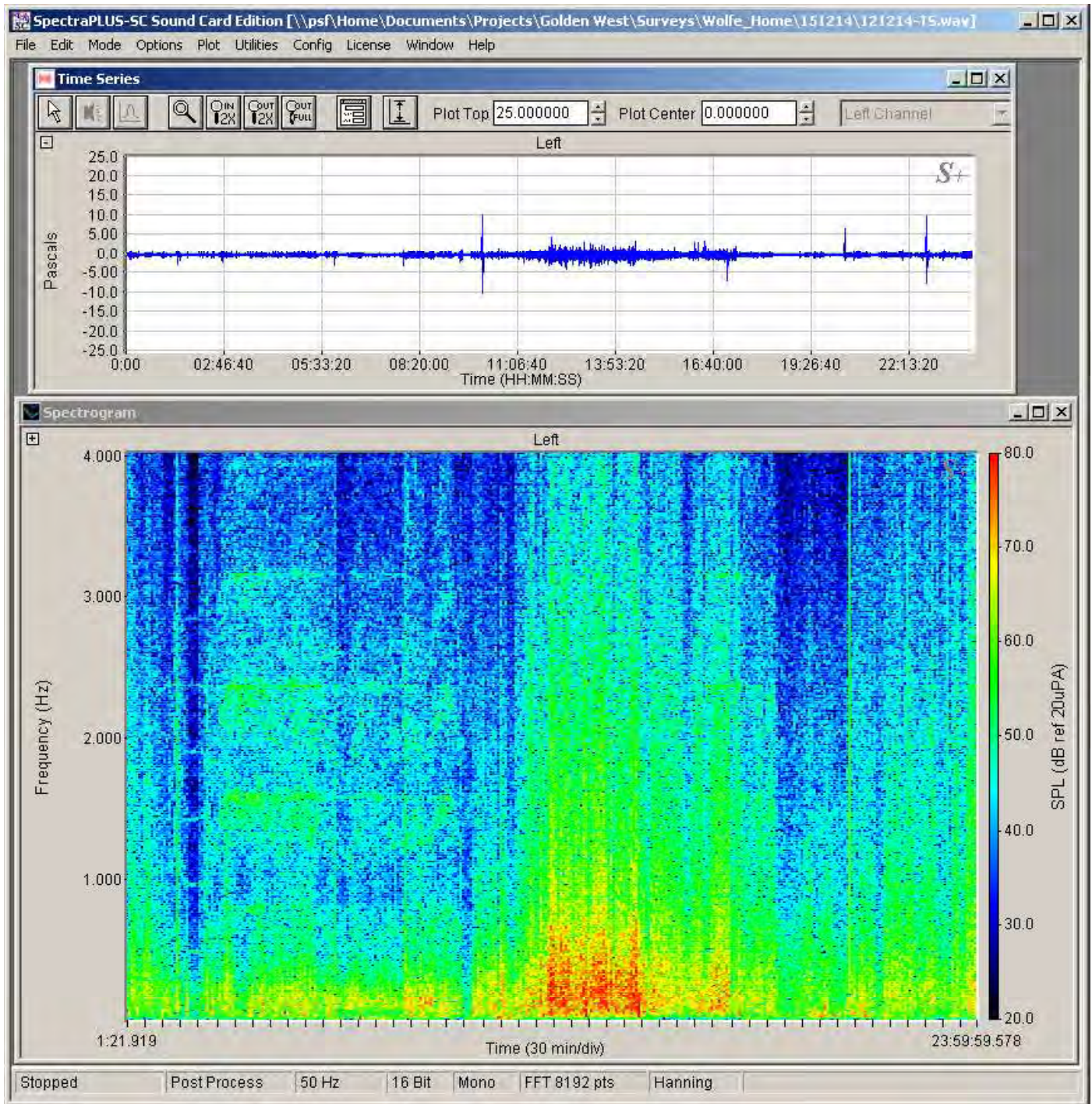
Location: WOLFE HOME

Date: 12/13/2015



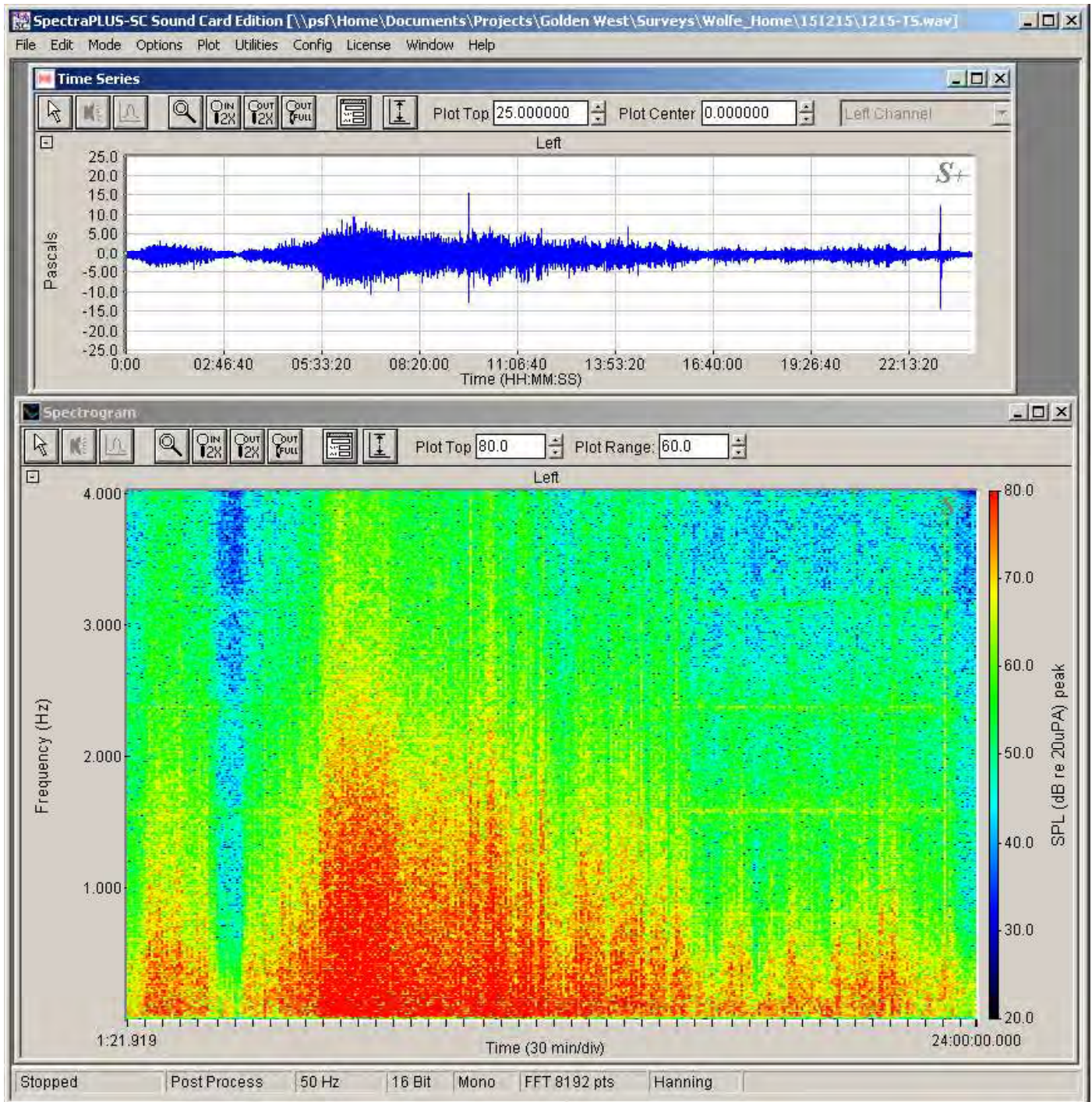
Note: Horizontal traces indicate wind turbine rotation. Rotation was observed at 0.79 Hz (15.8 rpm).

Location: WOLFE HOME
Date: 12/14/2015



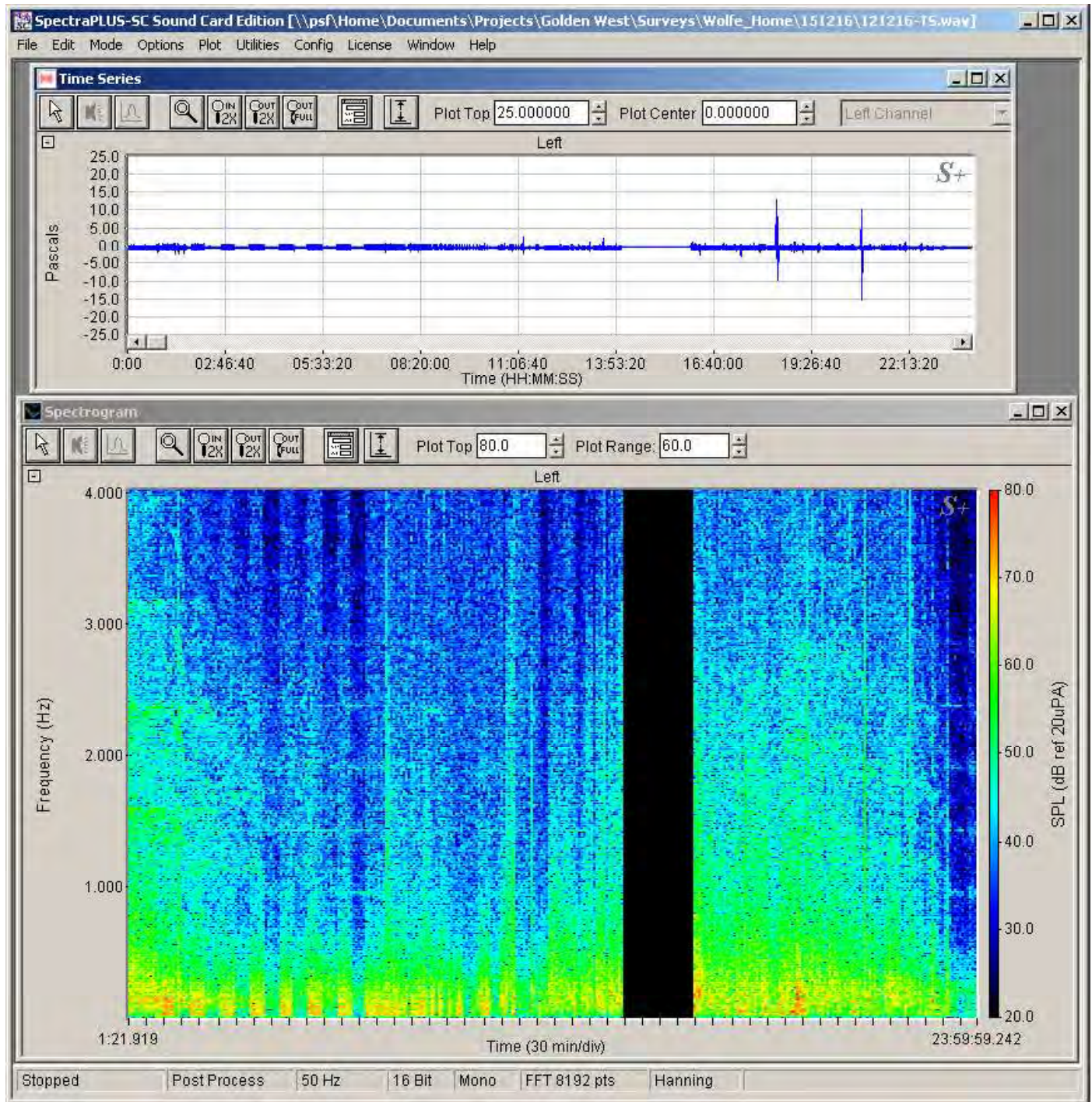
Note: Horizontal traces indicate wind turbine rotation. Rotation was observed at 0.48 Hz (9.6 rpm) prior to 2 AM rising to 0.79 Hz (15.8 rpm) until 9:30 AM when traces drop away. The 0.79 Hz trace harmonics were faintly visible between 12 PM and 6:20 PM and between 10 and 11 PM.

Location: WOLFE HOME
Date: 12/15/2015



Note: Horizontal traces indicate wind turbine rotation. Rotation was observed at 0.79 Hz (15.8 rpm) throughout the day however high wind levels on the house obscured details in the mid-day.

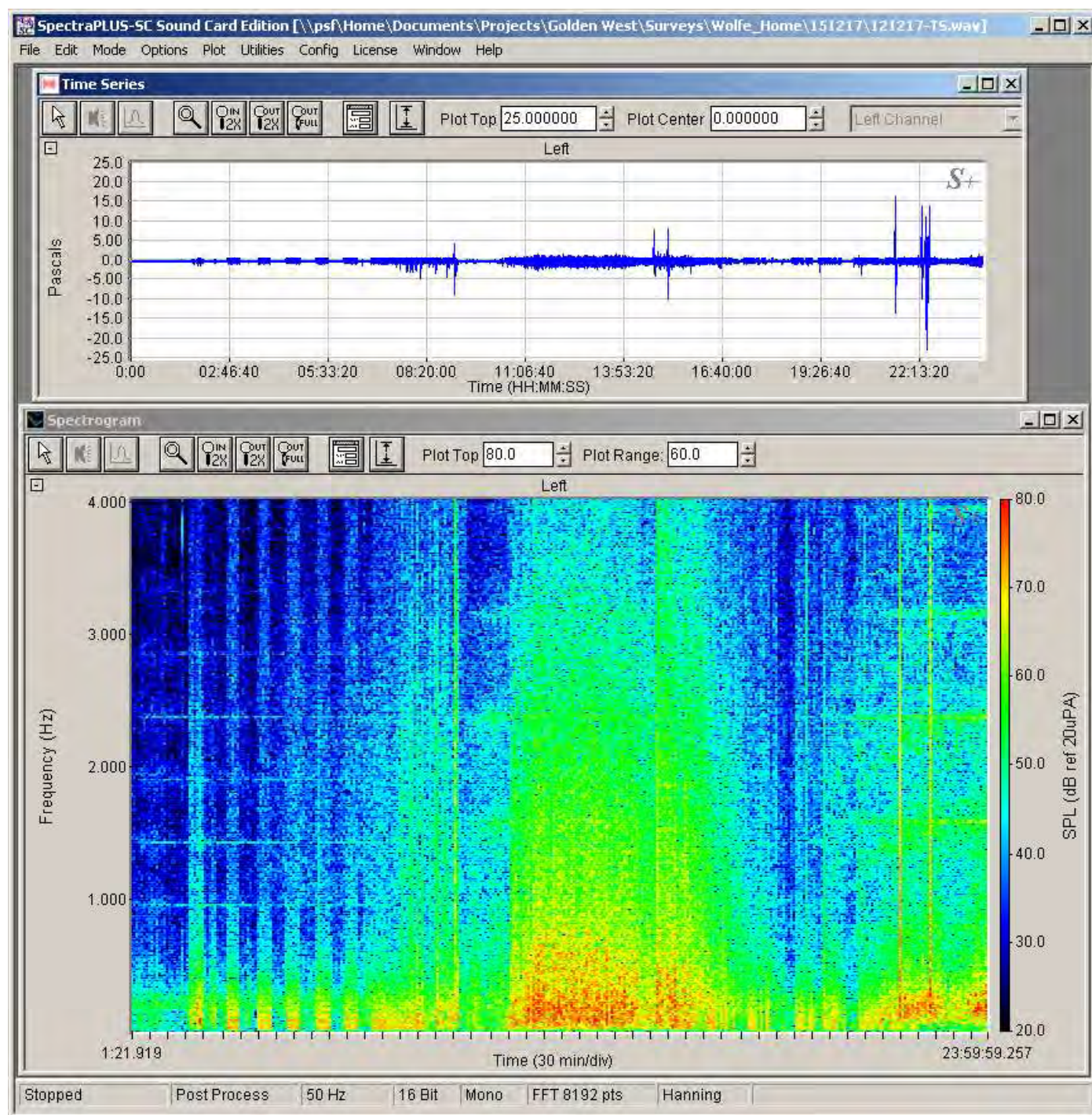
Location: WOLFE HOME
Date: 12/16/2015



Note: Horizontal traces indicate wind turbine rotation. Rotation was observed at 0.79 Hz (15.8 rpm) until about 2:30 AM, then at 0.48 Hz (9.6 rpm) until the mid-morning. System maintenance was performed from 2 to 4 PM. Multiple variable rotation rates were observed in the afternoon. Rotations dropped to 0.48 Hz (9.6 rpm) after 11 PM.

Location: WOLFE HOME

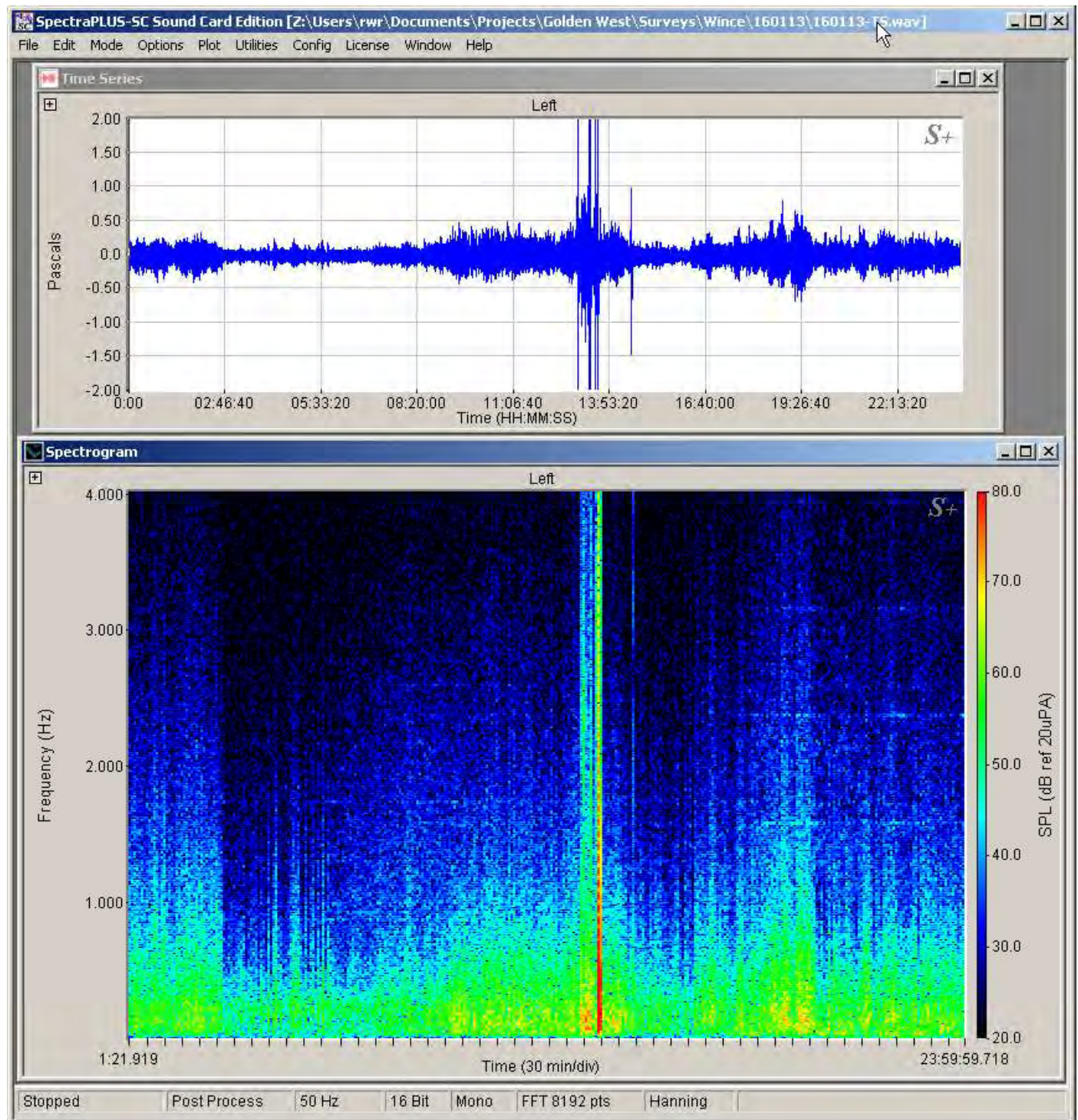
Date: 12/17/2015



Note: Horizontal traces indicate wind turbine rotation. Rotation was observed at 0.48 Hz (9.6 rpm) until about 9 AM when rotations increased to 0.78 Hz (15.8 rpm). Rotations vanished after 6 PM, and then reappeared at 0.78 Hz (15.8 rpm) after 7:20 PM.

Location: WINCE HOME

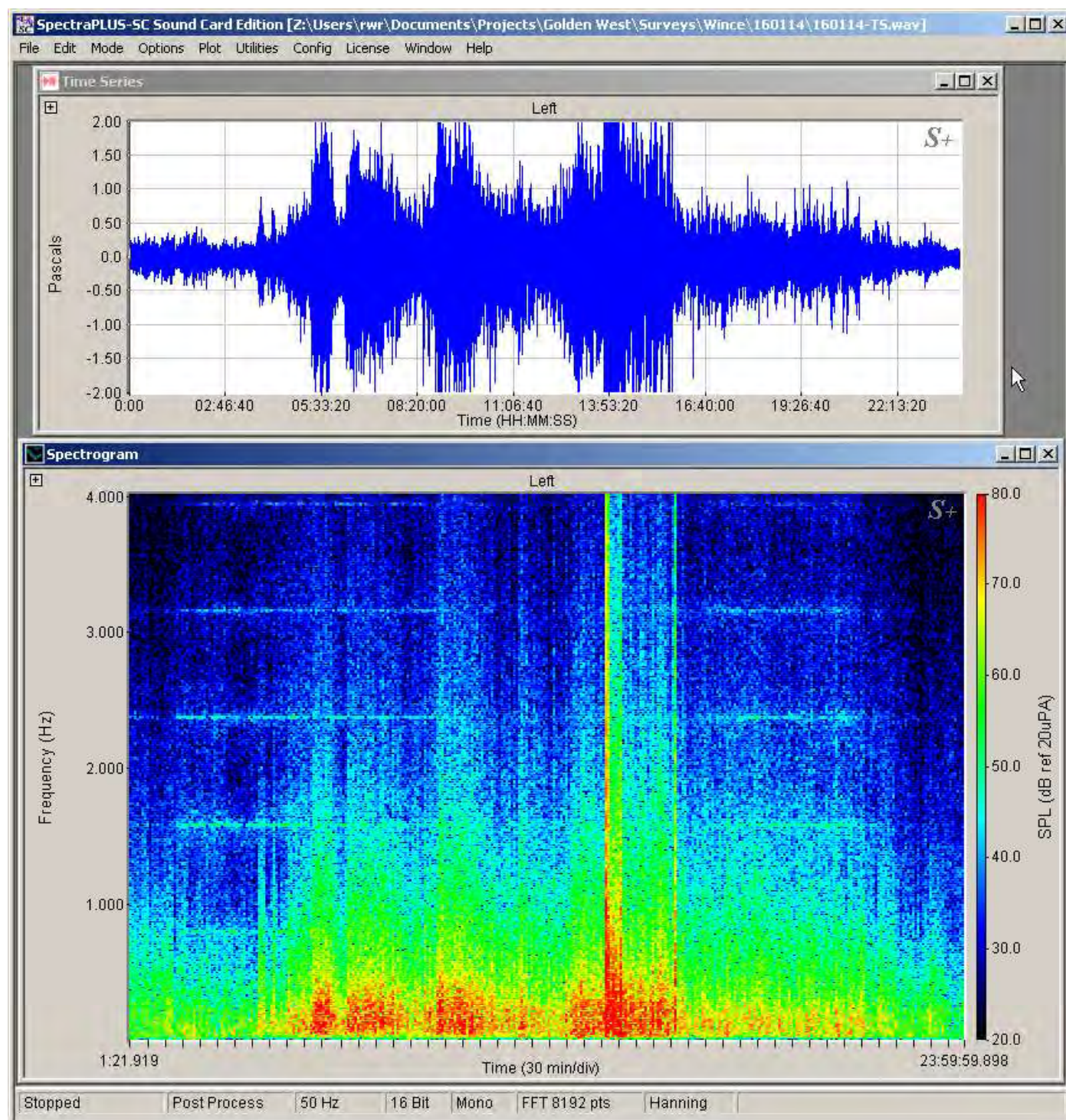
Date: 1/13/2016



Note: Horizontal traces indicate wind turbine rotation. Rotation at 0.79 Hz (15.8 rpm) observed. Traces consistent with wind direction; stronger when winds from W-NW, lighter when winds light or from other directions.

Location: WINCE HOME

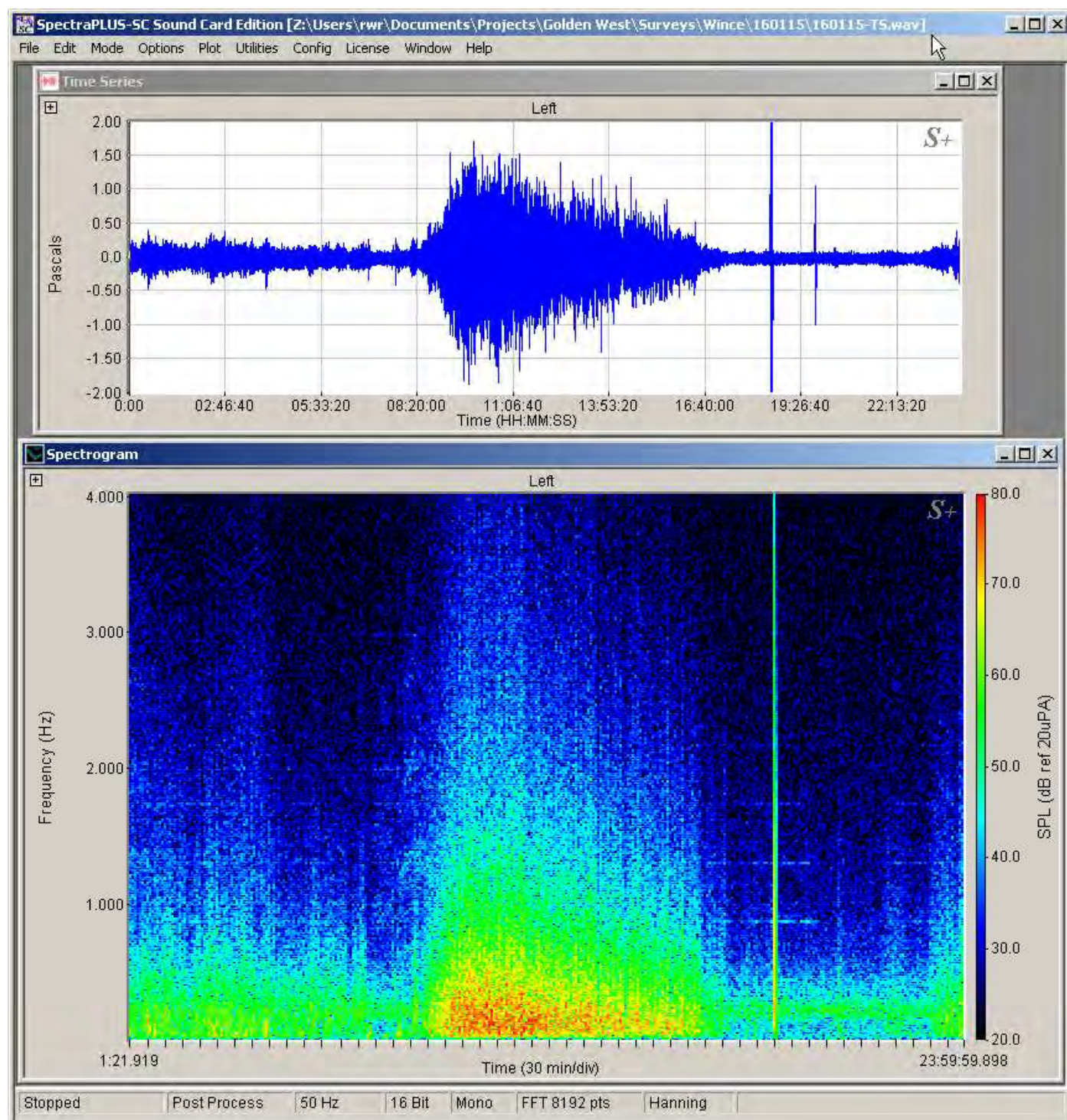
Date: 1/14/2016



Note: Horizontal traces indicate wind turbine rotation. Rotation at 0.79 Hz (15.8 rpm) observed. Traces consistent with wind direction; stronger when winds from W-NW, lighter when winds light or from other directions.

Location: WINCE HOME

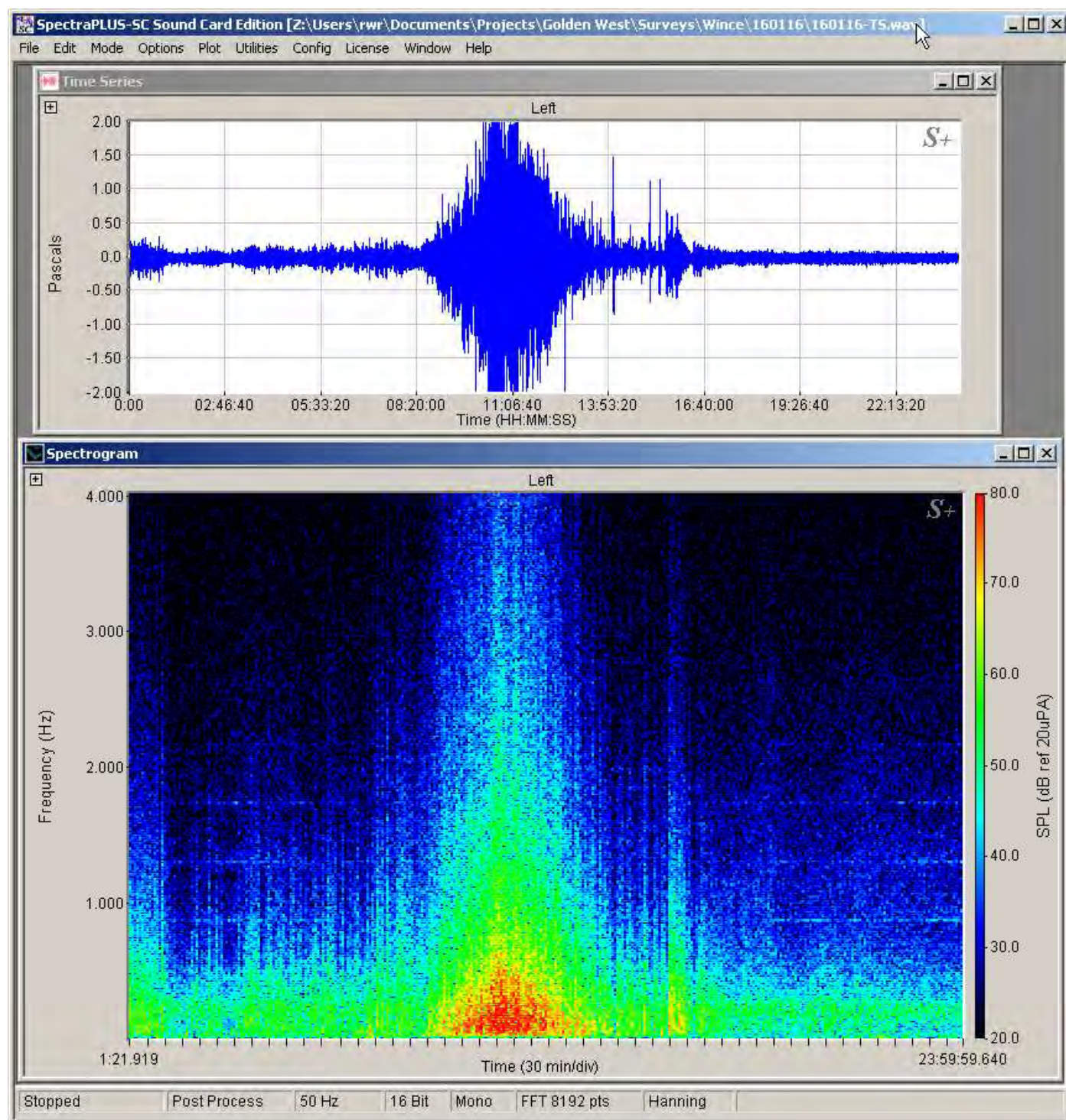
Date: 1/15/2016



Note: Horizontal traces indicate wind turbine rotation. Winds mid-day from east to south to west, dropping in strength. Rotation at 0.43 Hz (8.6 rpm) observed with light or no winds on ground.

Location: WINCE HOME

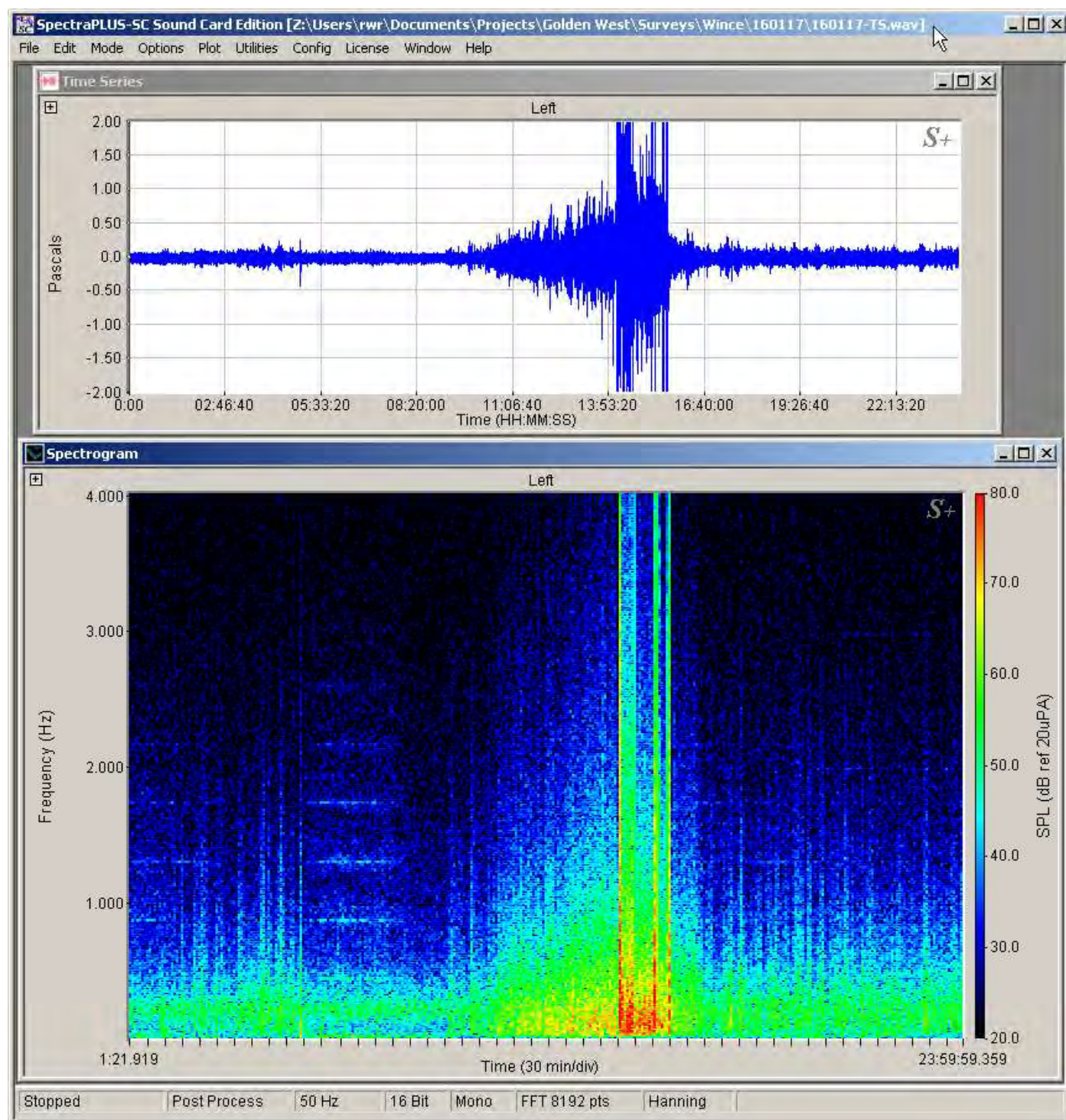
Date: 1/16/2016



Note: Horizontal traces indicate wind turbine rotation. Rotation at 0.43 Hz (8.6 rpm) observed.

Location: WINCE HOME

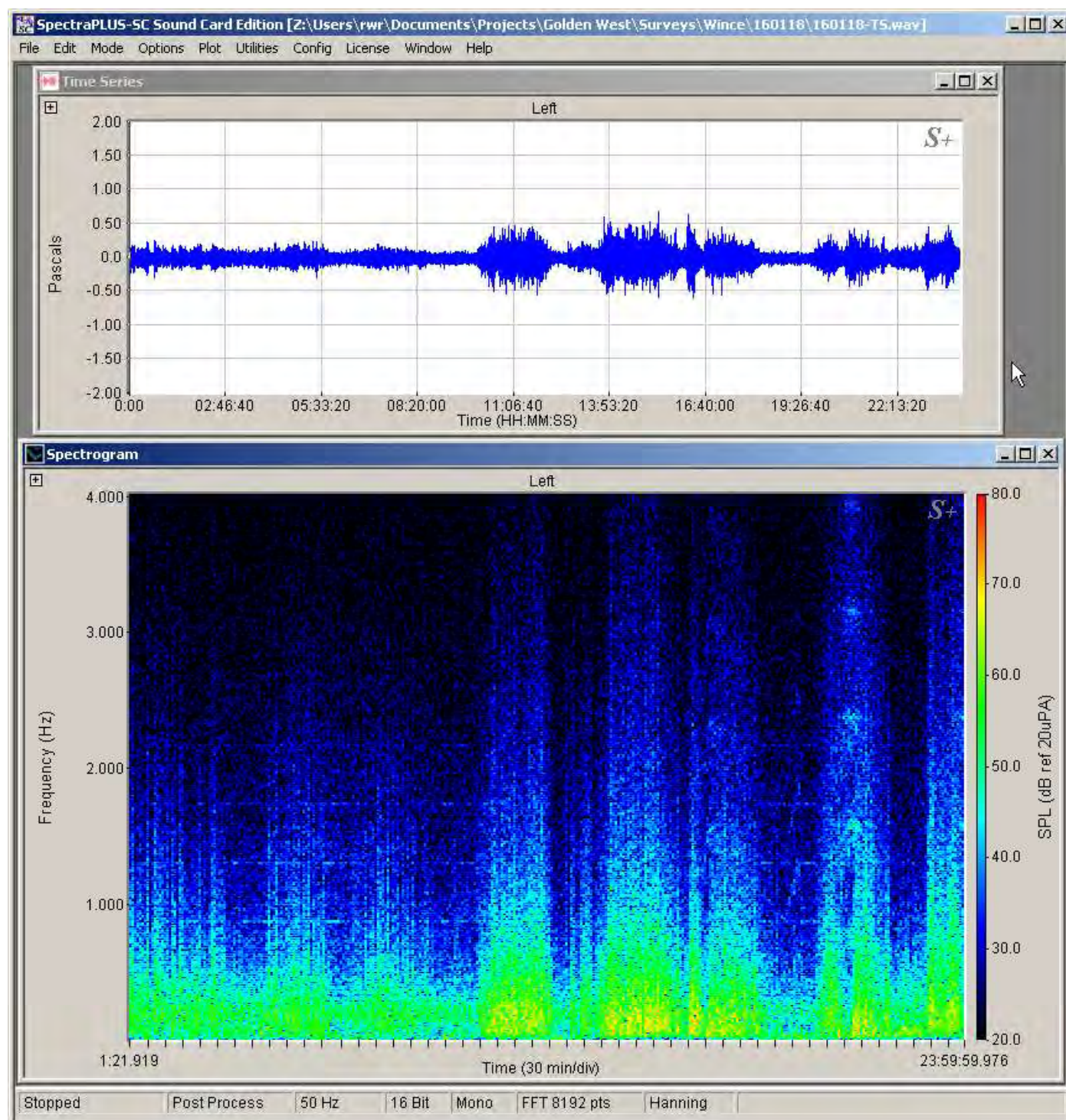
Date: 1/17/2016



Note: Horizontal traces indicate wind turbine rotation. Rotation at 0.43 Hz (8.6 rpm) observed.

Location: WINCE HOME

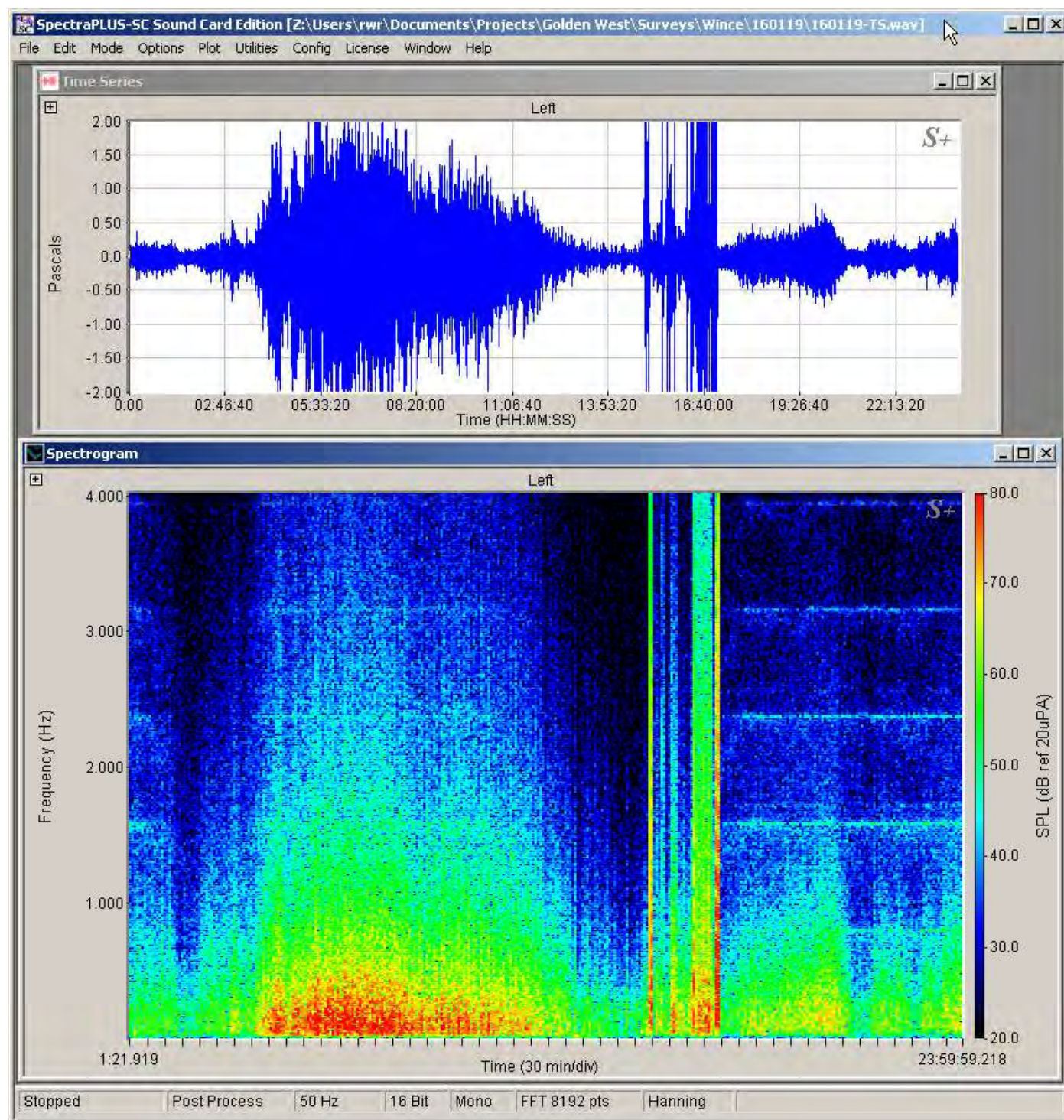
Date: 1/18/2016



Note: Horizontal traces indicate wind turbine rotation. Rotation at 0.43 Hz (8.6 rpm) observed and a strong surge up to 0.79 Hz (15.8 rpm) in late evening.

Location: WINCE HOME

Date: 1/19/2016



Note: Horizontal traces indicate wind turbine rotation. Rotation at 0.79 Hz (15.8 rpm) observed during winds from W-NW.