MG Acoustics

Analysis, Modeling, and Prediction of Infrasound and Low Frequency Noise from Wind Turbine Installation

Phase 2: Southern Ontario Site

Final Report

Please note that, in accordance with the provisions of the Access to Information and Privacy Act these documents have been redacted to protect confidential business information and the identity of study participants.

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I. INTRODUCTION

Health Canada is working with Statistics Canada and other external experts possessing expertise in areas including noise, health assessment, clinical medicine and epidemiology, on a research study that will explore the relationship between wind turbine noise and the extent of health effects reported by, and objectively measured in, those living near wind power developments. Health Canada, in collaboration with Statistics Canada, is undertaking a cross-sectional field study to evaluate these self-reported health impacts and symptoms of illness against objective biomarkers of stress and the sound levels generated by wind turbines, including low frequency noise. This data will be correlated with calculated wind turbine noise so that any potential relationship to reported health symptoms can be reliably determined.

The calculation of wind turbine noise over long distances presents a challenge. Most engineering methods to predict the propagation of sound, such as those found in commercial software packages, were essentially developed for industrial noise, road and rail traffic noise. This puts into question the use of commercial software to predict the propagation of infrasonic frequencies. For example, ISO 9613-2 is based on empirical corrections to inverse square law that are valid only down to 63 Hz; as well, ISO 9613-2 cannot accommodate specific sound speed profiles. More recent engineering methods such as the Nord2000 and the Harmonoise P2P models (implemented in commercial packages such as SoundPlan and CadnaA) are more powerful and can accommodate a number of simplified sound speed profiles. However, as part of an effort to reduce computational time, approximations are made – these approximation works at higher frequencies but their validity below 25 Hz has not been established. Wind turbines are known to radiate significant noise at very low frequencies, down to the "blade passage frequency" (typically 0.5-0.7 Hz). The use of commercial software to calculate noise propagation at these frequencies must be validated.

On the other hand, powerful computational models have been developed that can accommodate any arbitrary sound speed profile at all frequencies. Examples of such computational models are the Parabolic Equation (PE) and the Fast Field Program (FFP). Both the PE and the FFP are based on a numerical solution to the wave equation. These methods have been discussed in the Phase 1 report. They are known to be accurate and generally applicable, and can be used to provide baseline results against which commercial software can be tested.

It is the purpose of this current Phase 2 study to use the FFP method to generate propagation results for a well-defined generic test site under specific meteorological conditions. Health Canada will be able to perform comparable calculations using their commercial software and, hence, enable a comparison.

MG Acoustics has carried out the analysis, modeling, and prediction of infrasound and low frequency noise from wind turbines at two different sites, as part of the Health Canada study. This work has been divided into two parts, Phase 1 and Phase 2, associated with a Prince Edward Island site and a Southern Ontario site, respectively. There are several overall objectives:

- investigate the use of Harmonoise/Nord2000 weather classes with Environment Canada weather data to predict sound speed profiles

- investigate methods to separate low-frequency wind turbine noise from other sources of noise
- investigate the directivity of wind turbine noise sources at infrasonic frequencies
- compute wind turbine noise sound pressure levels at long range using state-of-the-art methods [e.g., Parabolic Equation (PE) and Fast Field Program (FFP)], to guide Health Canada in their use of Harmonoise P2P for predicting wind turbine noise propagation

Infrasound and low frequency noise from two wind turbine sites (PEI and Southern Ontario locations) has been addressed. This work allows Health Canada to evaluate whether or not infrasound and/or low frequency noise (from wind turbines in the locations specified) can be detected at different distances; and secondly to determine whether the Parabolic Equation method of calculation gives an adequate explanation of the experimental values with regards to infrasound and/low frequency and distances at which it can be detected. Thirdly, the results should allow Health Canada to reliably make infrasound and low frequency noise predictions (using Harmonoise) at southern Ontario sites.

The work has been completed in two phases:

1st Phase – Analysis of infrasound and low frequency noise measurements and analysis of meteorological data will be completed including the generation of theoretical predictions at the PEI site. This phase of the project has been described in the report "Analysis, Modeling, and Prediction of Infrasound and Low Frequency Noise from Wind Turbine Installation. Final Report (revised). Phase 1: PEI Site", submitted in February 2014.

2nd Phase – Modeling has been carried out and applied to wind turbines sites in southern Ontario. The procedures and results for this part of the study are discussed in this current report.

For this second phase, Health Canada chose not to specify a specific location of study. Instead, a generic site is considered. There are two main reasons for this approach. First, there was insufficient meteorological information available for some of the specific locations that might have been of particular interest. Second, the goal of this second phase is to enable a direct comparison of computational techniques (i.e., our state-of-the-art methods, PE and FFP, versus Health Canada’s use of Harmonoise P2P) and this is best accomplished assuming a generic site with well-defined terrain characteristics and prescribed meteorological conditions.

This current Phase 2 report, then, summarizes sound propagation calculations for a generic Southern Ontario site. The full-wave solutions are generated using the FFP approach and provide baseline targets that can be used in assessing the applicability and accuracy of commercial software packages that Health Canada is planning to use.

II. SOUTHERN ONTARIO WIND TURBINES

A. Location of Southern Ontario Wind Turbines

Health Canada chose not to specify a specific wind turbine site for study. Rather, a generic site with well-defined topological and meteorological characteristics would be adopted. It was agreed during discussions between MG Acoustics and Health Canada that a single wind turbine on flat ground would be assumed. Flat ground is also representative of large areas of agricultural land in Southern Ontario. Various "worst case" meteorological situations will be considered. It was agreed that MG Acoustics would compute color plots showing the noise radiation over a 10 km × 10 km grid.

B. Wind Turbine Noise Generation

For the noise calculations, the strength of noise generation at various frequencies is required. It will be assumed that our source is a wind turbine comparable to the [redacted]-[redacted] that was studied in Phase 1 of this project. The source levels observed on 21 November 2013 at 125 m will be used as the basis for our calculations. The levels used are tabulated in Table 1.

TABLE 1. Source levels used for the calculations

Frequency (Hz)	Level (dB)
1.61	65.6
3.22	61.7
4.83	53.9
6.45	46.4
20	52.3
45	46.5
70	33.3

Noise spectra were obtained (see report Phase 1) with a frequency resolution of 0.0244 Hz. The key spectral peaks were used to determine the levels.

III. GENERATION OF METEOROLOGICAL STATISTICS

Health Canada has expressed interest in generating yearly meteorological statistics to enable calculation of average noise levels. Some commercial noise propagation models have this computational feature -- however, they require as input the appropriate meteorological data, i.e., a weather statistics table. In this section, a procedure for generating a weather statistics table will be presented.

There are different approaches that could be taken to generate a weather statistics table but whether or not they can be used depends on what meteorological data is available. As a minimum, one requires wind speed and direction (at one height, preferably 10 m) every hour over a period of at least one year. Similarity theory can be used if temperature readings are available at two heights (e.g., 2 m and 10 m). As it is unlikely that such information would be available generally, this option will not be considered further. Alternatively, if cloud cover information is available, then a procedure described by Eurasto (2006) can be used. This procedure has been adopted for the Nord2000 and Harmonoise projects and is implicit in some commercial software packages (SoundPlan and CadnaA). This will be our focus here.

A. Overview of Approach

The effective speed of sound $c(z)$ depends on the height z above ground. Variations of sound speed with height cause sound to curve upwards or downwards which strongly affects the sound levels at a receiver. These variations are due to variations in both wind velocity and temperature. As discussed in the Phase 1 report, the sound speed profile can be approximated by the following equation,

$$c(z) = c(0) + B\ln\left(\frac{z}{z_0} + 1\right) + Az \quad ,$$

where z_o is a parameter known as the surface roughness. The parameters A and B are the key quantities needed for the weather statistics table.

Over the course of a year and hourly to hourly, the meteorological parameters are changing with time t. An understanding of how the weather statistics table arises and how it can be used is obtained by considering the parameters generally in their functional form. The parameter A varies with time and also depends on the wind direction $\theta_w(t)$ and on the sound propagation direction θ_{prop}. The parameter B behaves similarly. We write:

$$\begin{aligned} A &= A(t,\, \theta_w(t), \theta_{prop}) \\ B &= B(t,\, \theta_w(t), \theta_{prop}) \end{aligned} \quad .$$

At each instant in time, the A and the B control the sound propagation and determine the sound pressure level L that would be measured at a receiver. Functionally, this level can be expressed as

$$L = L\,(A\,(t,\,\theta_w(t),\theta_{prop}),\,B\,(t,\,\theta_w(t),\theta_{prop})\,)\ \ .$$

Over a long period of time *T*, the levels obtained must be averaged to give the long-term sound pressure level. An "energy average equivalent" is appropriate, leading to a L_{eq} level which can be expressed as

$$L_{eq}(\theta_{prop}) = 10\,\log_{10}\left\{\frac{1}{T}\int_0^T dt\,10^{\frac{L\,(A\,(t,\,\theta_w(t),\theta_{prop}),\,B\,(t,\,\theta_w(t),\theta_{prop})\,)}{10}}\right\}\ .$$

Eurasto (2006) found that a further simplification could be applied that still permitted accurate evaluation of L_{eq}. Only a small number of specific values of *A* and *B* needed to be considered. He suggests values of (-1, -0.4, 0, 0.4, 1) for *A* and values of (-0.12, -0.04, 0, 0.04, 0.12) for *B*. This gives 25 possible meteorological classes. The instantaneous *A* and *B* are rounded off to the nearest (A_m, B_n). For each of the meteorological classes, the corresponding sound pressure level is computed for each propagation direction θ_{prop} as

$$L\,(A_m(\theta_{prop}),\,B_n(\theta_{prop}))\ \ .$$

Typically, the propagation direction would be specified to the nearest 10°. There are then 25×36=900 calculations to perform, but these are each done just once and saved and recalled when necessary.

Let $p_{m\,n}$ be the fraction of time that the meteorological class (A_m, B_n) occurred, for each propagation direction. Then, the equation for L_{eq} can be rewritten as

$$L_{eq}(\theta_{prop}) = 10\,\log_{10}\left\{\sum_{m=1}^{5}\sum_{n=1}^{5}\,p_{m\,n}(\theta_{prop})\,10^{\frac{L\,(A_m(\theta_{prop}),\,B_n\,(\theta_{prop})\,)}{10}}\right\}\ .$$

In the commercial software SoundPLAN, the Nord2000 weather statistics table gives the values of $p_{m\,n}(\theta_{prop})$ appropriate to the local site. It is presumed that the CadnaA software uses something comparable.

To apply this method, the occurrence fractions $p_{m\,n}(\theta_{prop})$ must be computed for the local site using long-term meteorological information. This information, once compiled, constitutes the weather statistics table. Then, the equation above can be applied and the noise levels computed for each propagation direction.

B. Generation of a Weather Statistics Table

A source of meteorological data must be available. For generation of a weather statistics table as described for Nord2000 and Harmonoise, temperature, wind speed and direction, and cloud cover for an entire year or more are required. A convenient source of such information is the Environment Canada Weather Archives, although cloud cover is available only for certain weather stations.

At each time through the year, observations of wind speed yield a wind class W1 to W5. The fraction of cloud cover yields a stability class S1 to S5. Tables 2 and 3 below define these classes.

TABLE 2. Wind speed classification

wind speed component at 10 m above ground	wind speed class
0 to 1 m/s	W1
1 to 3 m/s	W2
3 to/ 6 m/s	W3
6 to 10 m/s	W4
> 10 m/s	W5

TABLE 3. Classification of atmospheric stability

time of day	cloud cover	stabilility class
day	0/8 to 2/8	S1
day	3/8 to 5/8	S2
day	6/8 to 8/8	S3
night	5/8 to 8/8	S4
night	0/8 to 4/8	S5

Tables 4 and 5 are used to determine *A* and *B*, respectively.

TABLE 4. Determination of A

A	S1	S2	S3	S4	S5
W1	-0.45	-0.22	0	0.22	0.34
W2	-0.22+0.33 C	-0.11+0.33 C	0.33 C	0.11+0.33 C	0.22+0.33 C
W3	-0.11+0.75 C	-0.06+0.75 C	0.75 C	0.06+0.75 C	0.11+0.75 C
W4	-0.06+1.33 C	1.33 C	1.33 C	1.33 C	0.06+1.33 C
W5	2.17 C	2.17 C	2.17 C	2.17 C	2.17 C

TABLE 5. Determination of B

B	**S1**	**S2**	**S3**	**S4**	**S5**
W1	0.03	0.01	-0.01	0.05	0.12
W2	0.01 – 0.02 C	- 0.01 C	-0.01	0.01+0.03 C	0.05+0.06 C
W3	-0.02 C	-0.01 – 0.01 C	-0.01	0.04 C	0.01+0.07 C
W4	-0.01-0.01 C	-0.01	-0.01	-0.01	0.06 C
W5	-0.01	-0.01	-0.01	-0.01	-0.01

where

$$C = \cos(\theta_w - \theta_{prop}) \ .$$

The wind direction is defined using the direction from which the wind is coming, measured clockwise from north, so that a wind blowing west to east will be 270°.

The instantaneous values of A are collapsed into the appropriate meteorological class A_m using Table 6.

TABLE 6. Meteorological class A_m

	A_1	A_2	A_3	A_4	A_5
interval	$-\infty < A \leq -0.7$	$-0.7 < A \leq -0.2$	$-0.2 < A \leq 0.2$	$0.2 < A \leq 0.7$	$0.7 < A < \infty$
representative value	-1.0	-0.4	0	0.4	1.0

Similarly, the values of B are collapsed into the appropriate meteorological class B_n using Table 7.

TABLE 7. Meteorological class B_m

	B_1	B_2	B_3	B_4	B_5
interval	$-\infty < B \leq -0.08$	$-0.08 < B \leq -0.02$	$-0.02 < B \leq 0.02$	$0.02 < B \leq 0.08$	$0.08 < B < \infty$
representative value	-0.12	-0.04	0	0.04	0.12

As a result of the above procedures, at each time (nominally, each hour) there will be 36 values of A_m and B_n, corresponding to each propagation angle θ_{prop} between 0° and 350° in 10° steps.

The statistics over a long period of time (at least 1 year) are then accumulated. Data for daytime, evening, and nighttime can be treated separately, if desired or required. The number of times the combination (A_m, B_n) is obtained is determined and used to calculate the fraction of time $p_{m\,n}$ that this meteorological class occurs over a year. The result is the entry to be made into the weather statistics table.

An example of a completed table, taken from the Eurasto report, is shown below in Table 8. Note that 36 propagation directions are shown as columns labelled 0 to 350. Each entry gives the percentage of time that the meteorological class, shown in the 25 rows, occurs. The sum of the entries in each column is 100%.

TABLE 8. Completed table

Finland_D	%																																					
			0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350
class	A (log)	B (lin)																																				
1	-1,00	-0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
2	-1,00	-0,04	0,2	0,2	0,2	0,2	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,1	0,1	0,1	0,1	0,1	0,1
3	-1,00	0	22,0	22,7	23,3	23,7	22,4	20,5	18,3	17,4	14,4	11,2	9,1	7,1	6,2	5,2	4,6	4,2	4,6	4,8	5,0	5,2	5,0	6,0	7,4	7,8	7,9	8,9	9,2	8,9	10,1	11,1	12,3	14,1	15,4	17,9	20,2	21,2
4	-1,00	0,04	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
5	-1,00	0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
6	-0,40	-0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
7	-0,40	-0,04	2,6	2,7	2,8	2,6	2,5	2,4	2,3	2,3	1,8	1,5	1,5	1,6	1,5	1,4	1,4	1,5	1,6	1,7	1,8	2,0	2,1	2,0	2,1	2,4	2,5	2,4	2,4	2,3	2,2	2,3	2,1	2,0	2,0	2,3	2,7	2,7
8	-0,40	0	29,8	28,7	27,2	25,5	25,1	25,4	27,3	27,0	28,4	30,0	28,8	25,5	21,9	20,3	18,5	17,9	17,2	17,8	17,0	16,5	16,3	16,2	16,8	17,9	18,7	19,0	20,7	23,1	23,7	23,6	25,8	27,9	28,6	28,9	29,2	29,9
9	-0,40	0,04	1,8	2,0	2,0	2,2	2,3	2,5	2,5	2,5	2,5	2,4	2,2	2,1	2,2	2,4	2,4	2,5	2,3	2,1	1,8	1,7	1,6	1,8	1,8	1,7	1,7	1,7	1,6	1,7	1,8	1,9	2,0	2,0	1,9	1,8	1,7	1,8
10	-0,40	0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
11	0,00	-0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
12	0,00	-0,04	0,3	0,3	0,1	0,1	0,5	0,3	0,1	0,1	0,4	0,2	0,1	0,1	0,2	0,2	0,2	0,1	0,1	0,2	0,2	0,2	0,1	0,4	0,4	0,2	0,2	0,4	0,3	0,2	0,3	0,1	0,1	0,2	0,3	0,1	0,1	0,1
13	0,00	0	20,8	21,0	22,1	22,8	22,0	22,6	22,3	21,3	20,8	21,2	23,0	27,4	28,8	27,4	28,4	26,9	25,4	22,6	22,3	23,2	24,7	24,5	23,2	23,3	23,4	23,4	23,6	23,3	24,8	28,9	30,6	28,9	29,0	26,3	23,2	20,9
14	0,00	0,04	0,3	0,2	0,3	0,3	0,3	0,2	0,2	0,4	0,5	0,6	0,5	0,5	0,5	0,4	0,3	0,2	0,2	0,2	0,2	0,2	0,2	0,4	0,5	0,5	0,4	0,3	0,2	0,1	0,1	0,1	0,1	0,1	0,2	0,3	0,4	0,3
15	0,00	0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
16	0,40	-0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
17	0,40	-0,04	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
18	0,40	0	13,1	12,5	12,5	12,5	13,4	14,2	14,6	15,8	18,3	20,7	21,7	22,4	24,9	27,2	27,6	27,0	26,6	27,5	27,5	26,3	25,1	24,0	24,3	25,0	25,8	25,5	26,7	27,6	25,7	22,3	17,9	16,7	14,8	14,5	14,2	14,7
19	0,40	0,04	3,9	3,8	3,5	3,1	3,1	3,4	4,0	4,2	4,1	4,1	4,1	3,7	3,1	3,0	3,1	3,6	3,9	3,7	3,8	3,9	3,8	3,6	3,6	3,4	3,7	4,1	3,9	3,6	3,4	3,5	3,5	3,2	3,2	3,3	3,4	3,7
20	0,40	0,12	1,4	1,3	1,3	1,2	1,0	0,8	0,8	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,8	0,9	1,0	1,2	1,2	1,2	1,2	1,3	1,4	1,4	1,5	1,5	1,7	1,8	1,8	1,7	1,6	1,6	1,6	1,5	1,5
21	1,00	-0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
22	1,00	-0,04	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
23	1,00	0	3,1	3,6	3,6	4,4	5,7	6,0	6,3	7,2	7,0	6,4	7,3	7,9	8,9	10,5	11,2	13,7	15,7	16,7	17,4	18,1	18,1	18,2	17,0	15,0	13,1	11,8	8,9	6,5	5,2	3,7	3,2	2,4	2,4	2,2	2,8	2,7
24	1,00	0,04	0,8	0,9	1,2	1,5	1,5	1,4	1,3	1,0	1,0	0,8	0,7	0,9	1,2	1,3	1,6	1,5	1,5	1,6	1,7	1,6	1,7	1,6	1,5	1,5	1,2	1,0	1,1	0,9	0,8	0,7	0,6	0,7	0,6	0,5	0,5	0,5
25	1,00	0,12	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0

Fig. 1. An example of statistical weights for a period "Day" (presented as percentages).

C. Starting Point for Southern Ontario

As a starting point, the weather data archived for the [redacted] weather station can be used. Matlab code was written to collect hourly meteorological data from the Environment Canada website archive for station [redacted] Figure 1 shows a snippet of the data. For each hour of the day, we see temperature, wind speed, and wind direction, all measured at a height of 10 m. Temperatures are in degrees Celcius. Wind speeds have been converted to m/s. Wind direction indicates the direction from which the wind is blowing, relative to north (so 90° signifies a wind coming from the east). The values reported correspond to average readings over the two minutes preceding the hour. The cloud cover indicators correspond to the fraction of sky covered, as defined by:

0/10 : Clear
1/10 - 4/10 : Mainly Clear
5/10 - 9/10 : Mostly Cloudy
10/10 : Cloudy

[redacted]013.txt - Notepad

File Edit Format View Help

```
             20:00    20.4    70 15  Mainly Clear        3         ---
             21:00    19.1    70 13  Clear               3         ---
             22:00    17.7   130  7  Clear               2         ---
             23:00    17.1   110  6  Clear               2         5

                       T     deg  v   cloud cover    WindClass StabClass
11-Aug-2013  00:00    16.5   120  7  Clear               2         5
             01:00    15.5   ---  0  Clear               1         5
             02:00    15.2   ---  0  Mainly Clear        1         5
             03:00    15.3   ---  0  Mainly Clear        1         5
             04:00    14.9   ---  0  Mainly Clear        1         5
             05:00    14.8   ---  0  Mainly Clear        1         5
             06:00    14.9    10  6  Mostly Cloudy       2         ---
             07:00    17.2   100  6  Mostly Cloudy       2         ---
             08:00    19.7   120  6  Mostly Cloudy       2         ---
             09:00    22.5   160  6  Mostly Cloudy       2         ---
             10:00    22.5   260 11  Mostly Cloudy       3         ---
             11:00    23.2   190 15  Mostly Cloudy       3         2/3
             12:00    24.4   230 13  Mostly Cloudy       3         2/3
             13:00    23.9   220 17  Mostly Cloudy       3         2/3
             14:00    25.1   220 11  Mostly Cloudy       3         2/3
             15:00    25.1   240 19  Mostly Cloudy       3         2/3
             16:00    25.1   200  6  Mostly Cloudy       2         2/3
             17:00    25.2   220 11  Mainly Clear        3         1/2
             18:00    25.2   250  6  Mainly Clear        2         ---
             19:00    24.4   240 15  Mostly Cloudy       3         ---
             20:00    22.9   230  6  Mostly Cloudy       2         ---
             21:00    22.5   ---  0  Mostly Cloudy       1         ---
             22:00    22.2    80  4  Mostly Cloudy       2         ---
             23:00    22.2    80  4  Mostly Cloudy       2         4

                       T     deg  v   cloud cover    WindClass StabClass
12-Aug-2013  00:00    20.9   ---  0  Mostly Cloudy       1         4
             01:00    20.1   ---  0  Mostly Cloudy       1         4
             02:00    20.1   ---  0  Mostly Cloudy       1         4
             03:00    20.3   200  6  Mostly Cloudy       2         4
             04:00    20.5   ---  0  Cloudy              1         4
```

FIG. 1. Environment Canada data

The wind class is determined from Table 2 shown earlier. The stability class is determined, in part, from Table 3 shown earlier – there is a bit of a problem, though: the Eurasto scheme treats cloud cover as multiples of 1/8 whereas Environment Canada uses multiples of 1/10. There is some ambiguity in assignment of stability class. The data from [redacted] weather station between 1 January and 17 December 2013 was examined and yielded the distribution of weather classes shown in Table 9:

TABLE 9. Distribution of weather classes from [redacted] weather station

%	Stability Class					
Wind Class	S1	S1 or S2	S2 or S3	S3	S4	S5
W1	0.0	0.2	0.4	0.1	1.2	2.9
W2	0.6	2.7	3.9	1.0	7.5	12.0
W3	1.3	6.0	13.1	4.2	11.2	9.3
W4	0.5	3.0	8.6	2.8	4.4	1.3

W5	0.2	0.2	0.6	0.6	0.4	0.2

For a weather statistics table to be completed, the ambiguity in assigning stability class will need to be resolved. There are a couple other issues to address. At times, when there is rain or snow for example, there will be no cloud cover information – a decision will need to be made on how this weights the statistics. The assignment of stability class depends on whether it is daytime or nighttime – some consideration is needed to determine to which category a particular hour's data should be assigned, if at all.

No weather statistics table will be generated in this report. The intent is simply to indicate how such a calculation could be performed.

IV. NOISE PROPAGATION CALCULATIONS

For a study of the effects of infrasound from wind turbines, there is a need to predict the propagation of infrasonic frequencies over large distances. However, engineering methods to predict the propagation of sound, such as those found in commercial software packages, were essentially developed for industrial noise, road and rail traffic noise. This puts into question the use of commercial software to predict the propagation of infrasonic frequencies.

For example, ISO 9613-2 is based on empirical corrections to inverse square law that are valid only down to 125 Hz. Further ISO 9613-2 cannot accommodate a specified sound speed profile. More recent engineering methods such as the Nord2000 and the Harmonoise P2P models are more powerful. They can accommodate a number of simplified sound speed profiles. However, for computational purposes, a linear fit is forced to the observed profile. This is because when the sound speed profile varies linearly with height, all the sound rays are given by the roots of a quartic equation and individual rays can be simply summed to obtain the overall sound pressure levels. This approximation works at higher frequencies but its validity at low and infrasonic frequencies has not been established.

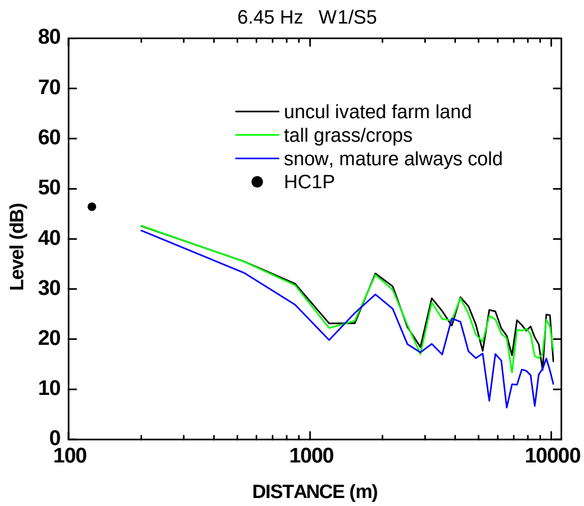
On the other hand, powerful computational models have been developed that can accommodate any arbitrary sound speed profile at all frequencies. Examples of such computational models are the Parabolic Equation (PE) and the Fast Field Program (FFP). Both the PE and the FFP are based on a numerical solution to the wave equation. These methods have been discussed in the Phase 1 report.

If commercial software is going to be used to predict infrasound propagation then it is imperative that their low-frequency predictions be validated against calculations using either the PE or FFP methods. In this section, we will use the FFP method to generate propagation results for a well-defined generic test site under specific meteorological conditions; Health Canada will be able to perform comparable calculations using their commercial software and, hence, enable a comparison.

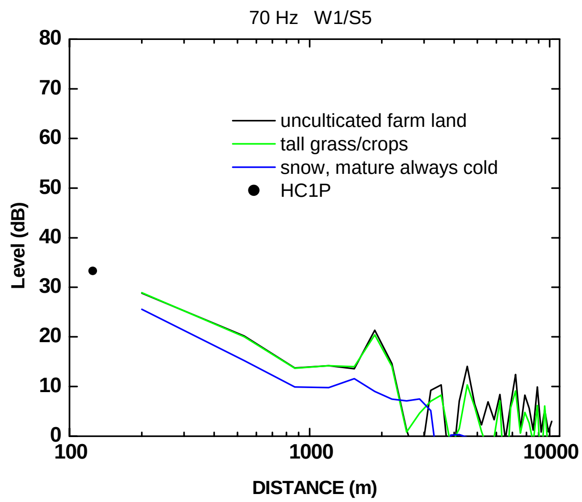
It was agreed that MG Acoustics would perform calculations for the “worst case” meteorological situations (i.e. conditions that are expected to lead to highest sound levels) and for frequencies below 100 Hz and down to the infrasonic frequencies. These “worst case” meteorological conditions occur during inversion or inversion plus downwind propagation conditions and correspond to weather classes having a positive Monin-Obukhov length: W1/S4, W2/S4, W3/S4, W1/S5, W2/S5, W3/S5 and W4/S5. Note that these seven weather classes occurred about 45% of the time in 2013 in the Windsor area.

As a first step, we must determine the sensitivity of the calculation to the type of ground cover. During the summer, the farm land will be covered with crops or tall grass. During a good part of the spring and fall, large portions of farm land will be uncultivated. During the winter, the ground will be frozen or partially frozen and often covered with a layer of snow. The snow cover can range from fresh snow to wind swept mature snow and also includes wet granular snow and ground only partially covered with snow (dry, wet or ice covered).

Figures 2 below shows calculated levels as a function of distance at 6.45 Hz and 70 Hz for three different types of ground cover. The data point at 125 m is a typical value from station HC1P and is used to the calculation. A stability class W1/S5 has been assumed and the propagation is directly downwind..



(a)



(b)

FIG.2. Effect of ground cover

It is noted that only when soft snow completely covers the ground do we find that the levels are slightly lower than the other two ground covers. This implies that the sound levels will be at their highest during most of the years, with the exception being during the days after a fresh snow fall followed by maturing without any melting.

A single wind turbine will be assumed to be radiating over flat ground. As the absolute "worst case", we will assume uncultivated farm land. Levels will be calculated as a function of distance and color plots showing the noise radiation over a 10 km × 16 km grid will be generated. The source is located at Easting 5 km and Northing 5 km on the grid. The calculations will be done at selected infrasonic frequencies (1.61 Hz, 3.22 Hz, 4.83 Hz, and 6.45 Hz) and at 20 Hz, 45 Hz, and 70 Hz. In all cases the wind will be assumed to be blowing due east from the source.

A. Weather classes

The temperature, wind speed and sound speed profile in the case of five stability classes are show in Figures 3 to 7 below.

Weather class W1/S4

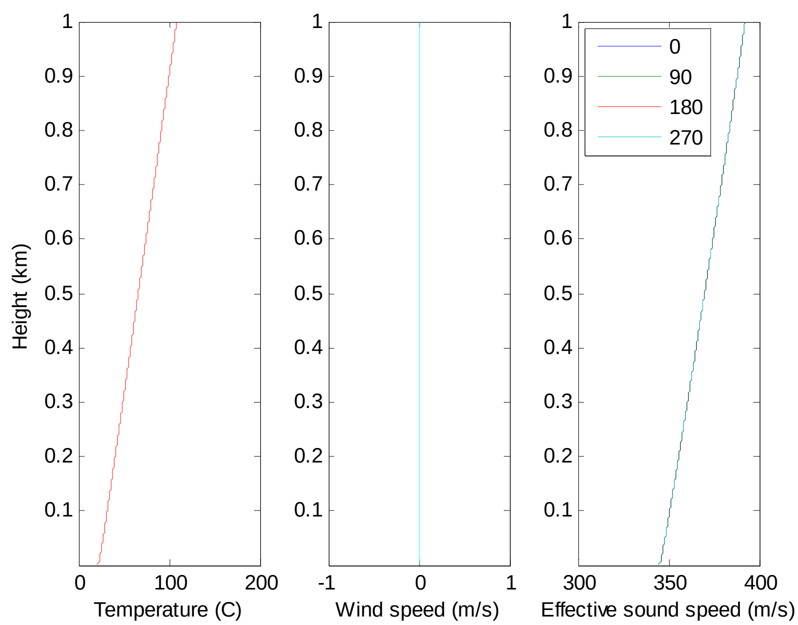


FIG. 3. Weather class W1/S4

This weather class corresponds to a temperature inversion with little to no wind.

In the right panel, here and for the following four figures, 0 deg is due east from the source and 180 deg is due west from the source. Since no wind is assumed in this calculation, there will be downward refraction in all directions from the source.

We note here that the temperature profile above 100 to 200 m is not realistic. This will be discussed in more detail in Section V.

Weather class W2/S4

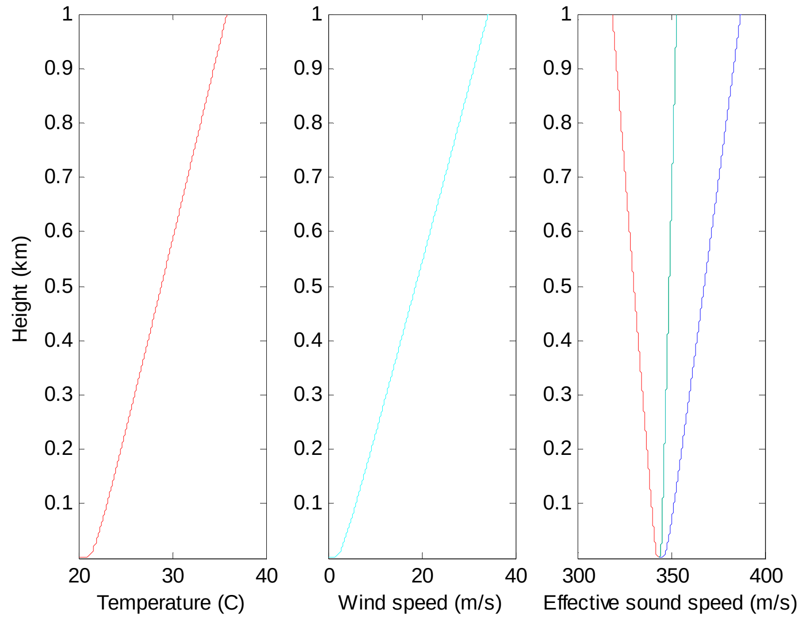


FIG. 4. Weather class W2/S4

For this weather class, there is still an inversion, but because of the wind there will be downward refraction east of the source (0 deg) and upward refraction west of the source (180 deg). Because of symmetry, the two crosswind sound speed profiles (90 deg and 270 deg) are the same.

We note that the sound speed profile resulting from weather class W3/S4 is virtually identical to those shown here for class W2/S4. Thus the weather class W3/S4 will not be considered further.

Weather class W1/S5

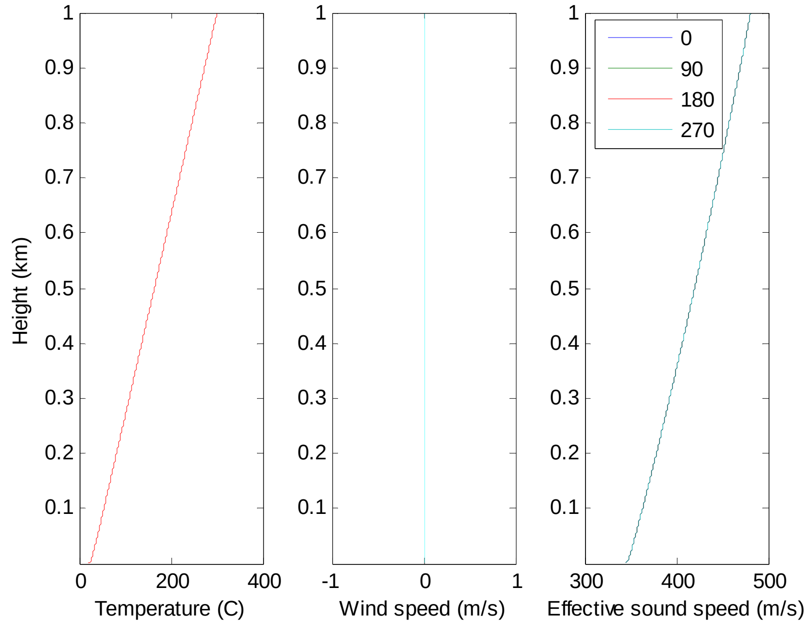


FIG. 5. Weather class W1/S5

This weather class corresponds to the strongest inversion with little to no wind. There will be downward refraction in all directions from the source.

We note also the temperature profile to totally unrealistic above 200 m (see Section V).

Weather class W2/S5

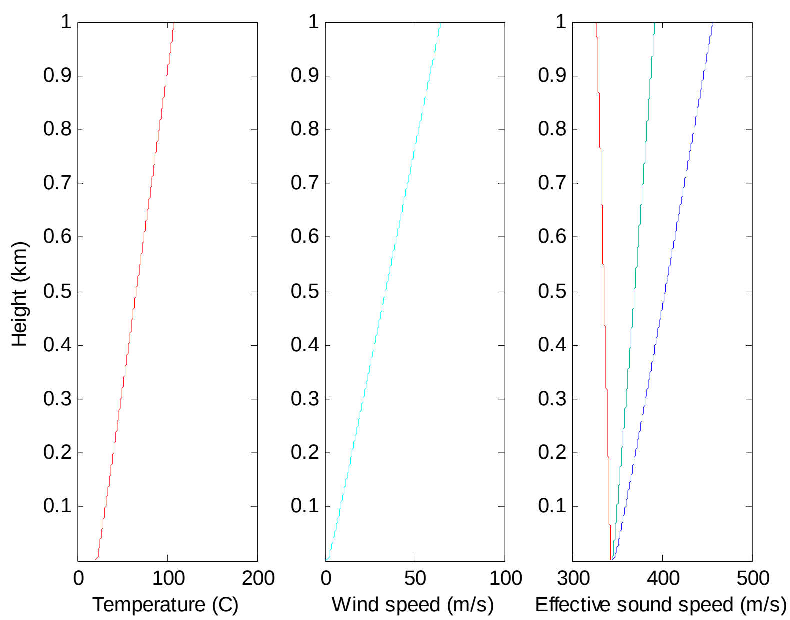


FIG.6. Weather class W2/S5

The temperature inversion is weaker, but still unrealistic above 200 m. Because of the wind speed profile, refraction will be downward east of the source and upward west of the source. North (90 deg) and south (180 deg) from the source there will be only weak downward refraction.

Weather class W3/S5

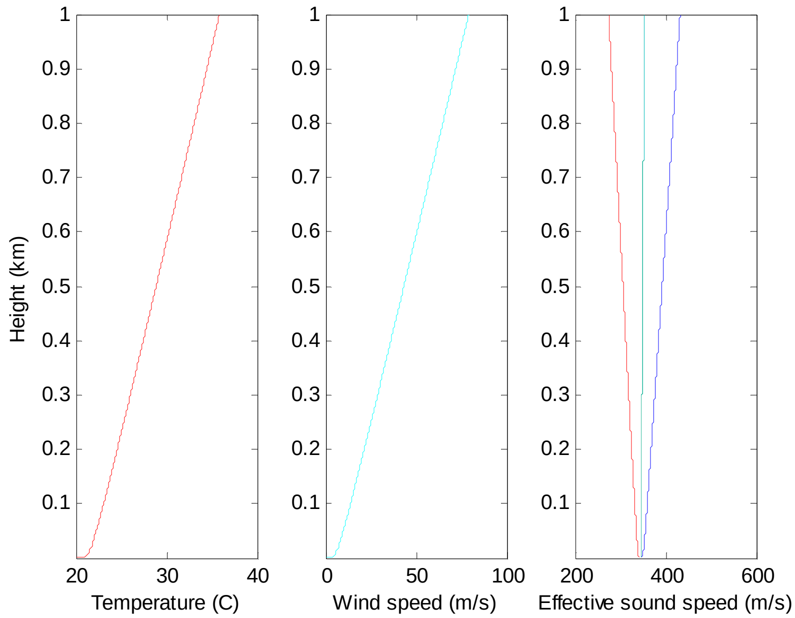


FIG. 7. Weather class W3/S5

There is still a mild inversion for this weather class. Given the wind speed and direction, downward refraction occurs east (0 deg) of the source while upward refraction occurs west (180 deg) of the source.

The sound speed profile resulting from the weather class W4/S5 is essentially the same as those generated here for class W3/S5. Thus, weather class W4/S5 will not be considered further.

B. Calculated levels and Transmission Loss

In this section, we compare calculated levels as a function of distance for each frequency and the five weather classes retained. The color plots for each weather class represent the transmission loss plotted as:

$$TL = L(1\,m) - L(\vec{r})$$

where $L(\vec{r})$ is the sound level at a field point and $L(1\,m)$ is the sound level at 1 m from the source. The sound pressure levels as a function of distance are thus obtained from the nominal levels measure at 125 m (from HC1P) and corrected for inverse square law back to the source position.

Note that in all the following figures, the same axis scaling was used for all frequencies and weather classes so that direct comparison can be made.

Frequency 1.61 Hz

The sound levels as a function of distance for a frequency of 1.61 Hz are shown below in Figure 8 for the five weather classes. Propagation is directly downwind as illustrated by the dotted line in Figure 9(a).

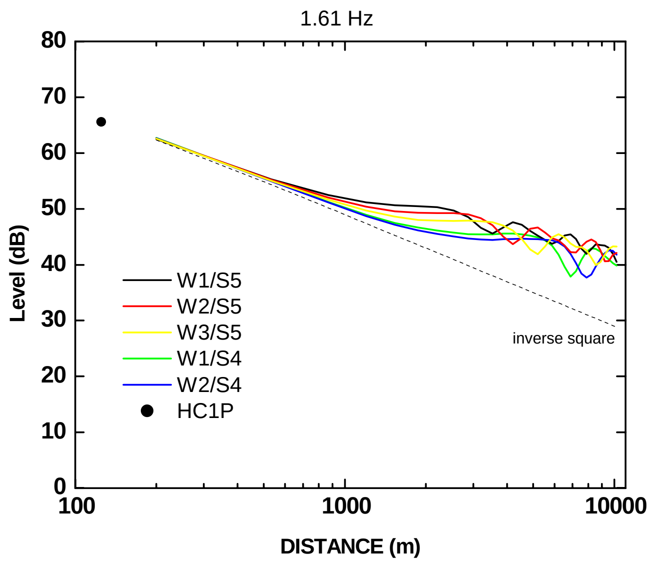
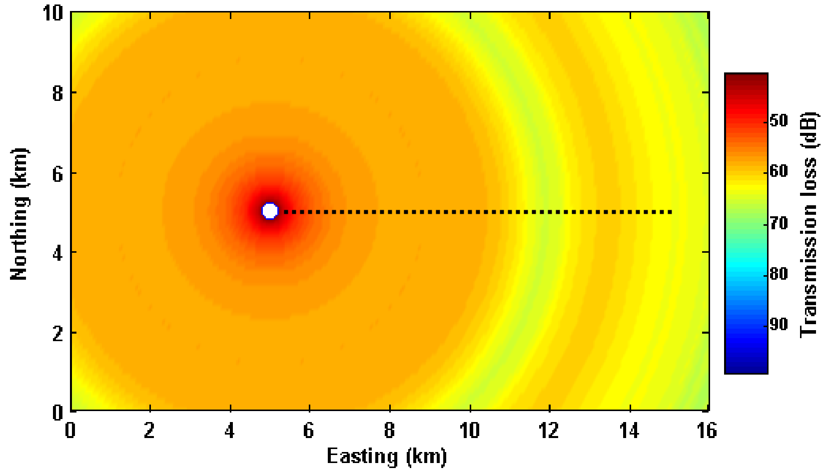


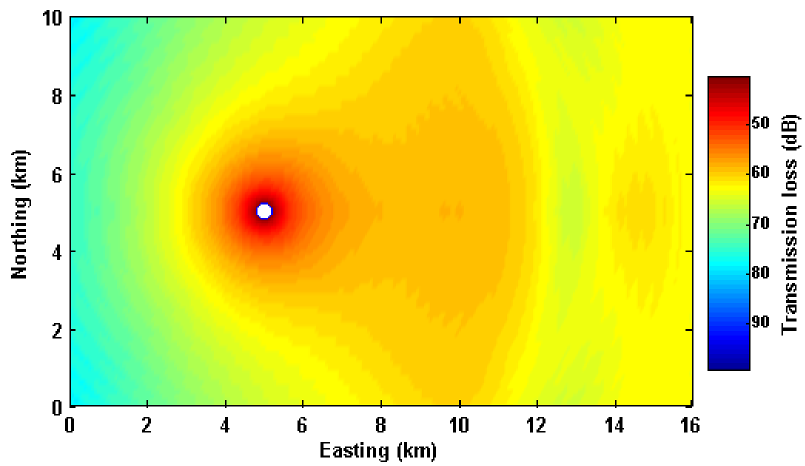
FIG. 8. Sound levels as a function of distance

Note that the curves for the various weather classes are quite similar. For comparison the levels from inverse square law are shown by the dashed line.

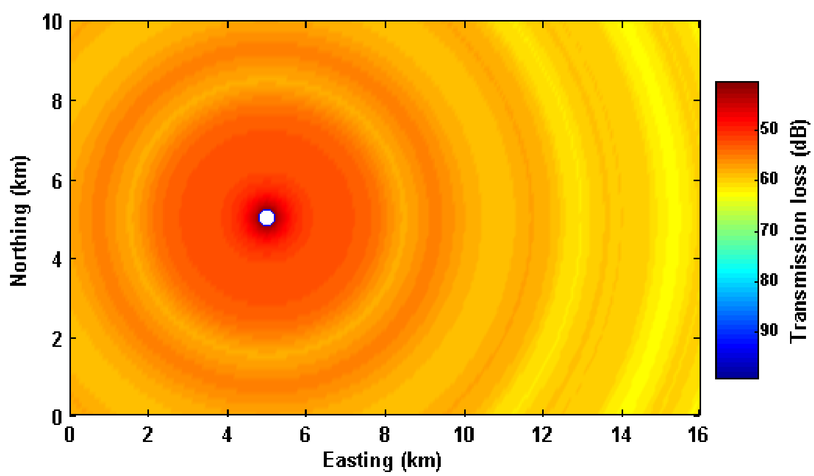
The color plots of the transmission loss for each of the five weather classes are shown below in Figures 9.



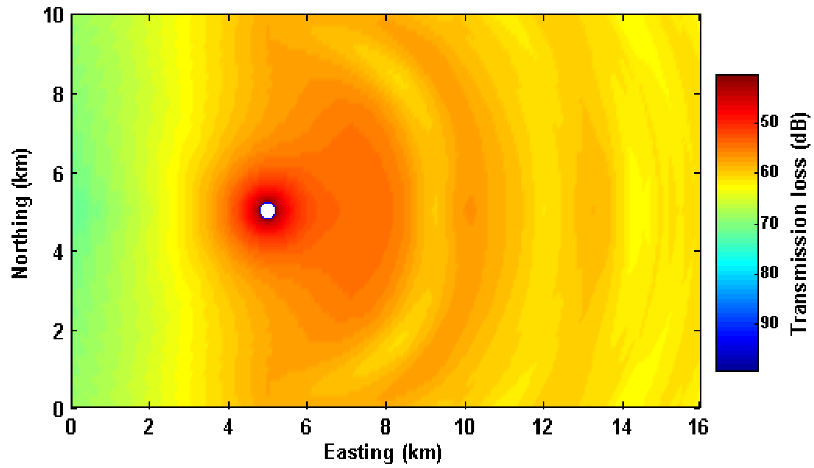
(a) W1/S4



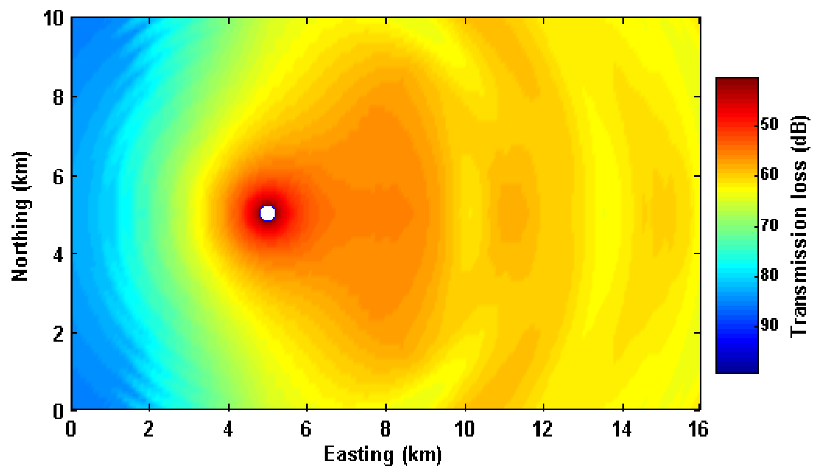
(b) W2/S4



(c) W1/S5



(d) W2/S5



(e) W3/S5

FIG. 9. Color plots of transmission loss

In the case of weather class W1/S4, the transmission loss decreases uniformly in all direction since this represents a temperature inversion with no wind.

For weather class W2/S4, one can clearly see the downward refraction towards the east due to the downwind propagation and the upward refraction due to the upwind propagation leading to greater transmission loss (lower sound levels) towards the west

Weather class W1/S5 is again a temperature inversion with no wind. The transmission loss is comparable to those obtained for weather class W1/S4 although there are differences in the fine details.

Weather class W2/S5 shows mild upward refraction west of the source.

The strongest upward refraction is obtained west of the source for weather class W3/S5.

Frequency 3.22 Hz

The sound levels as a function of distance for a frequency of 3.22 Hz are shown below in Figure 10 for the five weather classes.

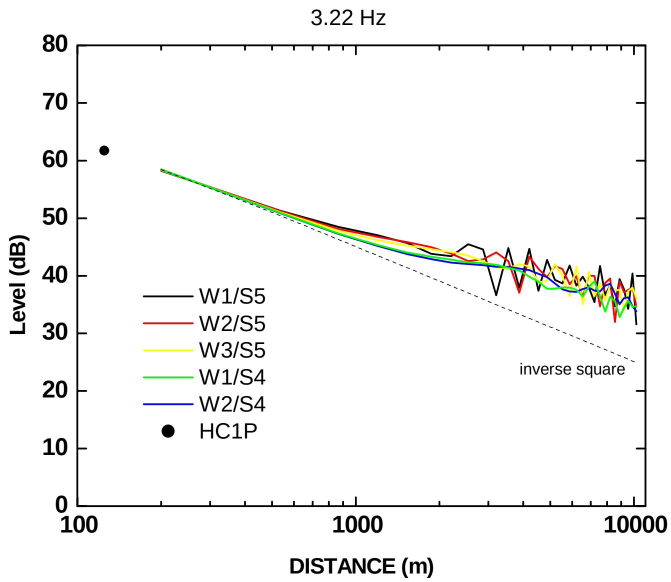
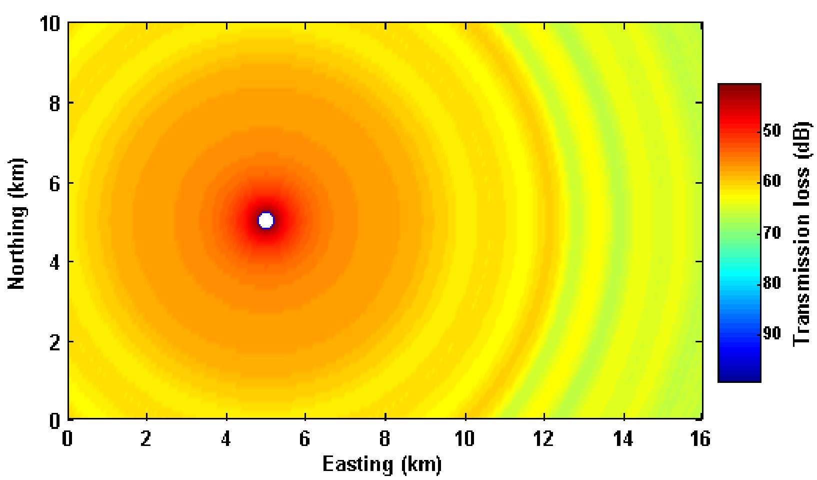


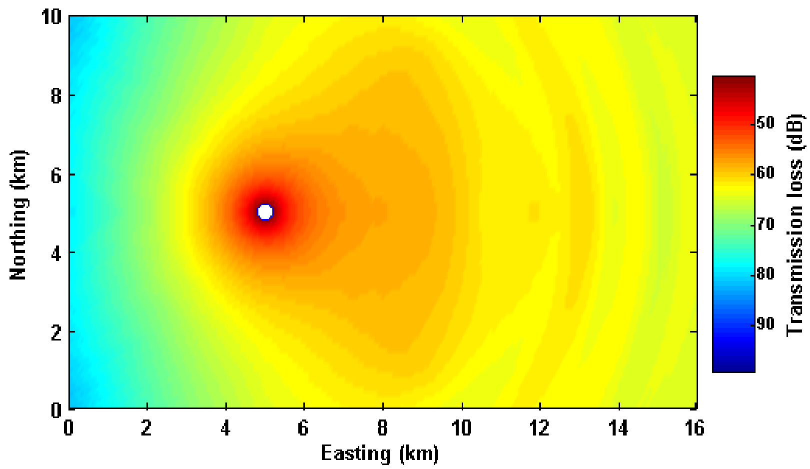
FIG.10. Sound levels as a function of distance

Again, no systematic differences are seen in the overall calculated levels for the five weather classes, but there are differences in the fine detail at the larger distances.

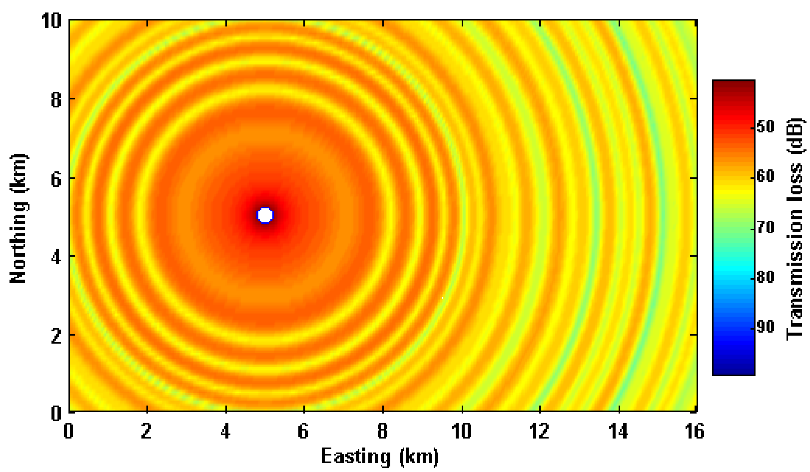
The color plots of the transmission loss for each of the five weather classes are shown below in Figure 11.



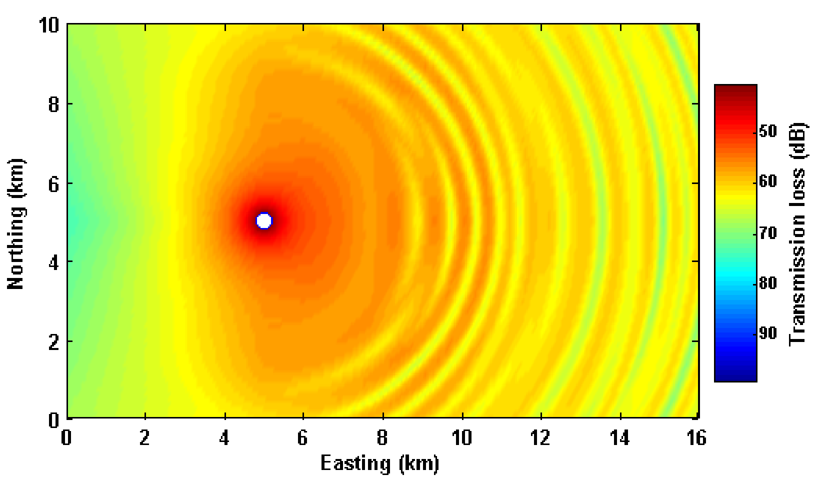
(a) W1/S4



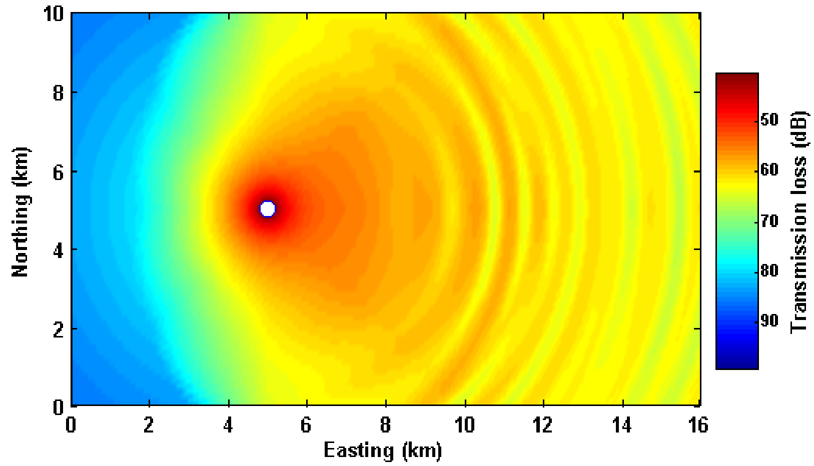
(b) W2/S4



(c) W1/S5



(d) W2/S5



(e) W3/S5

FIG. 11. Color plots of transmission loss

The transmission loss at this frequency is generally comparable to those obtained at 1.61 Hz. Note, however, the increasing amount of finer detail, especially for weather classes W1/S5 and W2/S5.

Frequency 4.83 Hz

The sound levels as a function of distance for a frequency of 4.83 Hz are shown below in Figure 12 for the five weather classes.

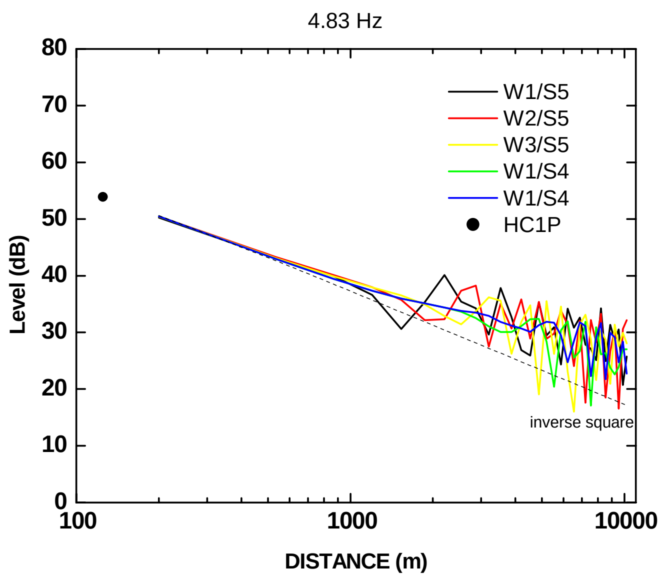
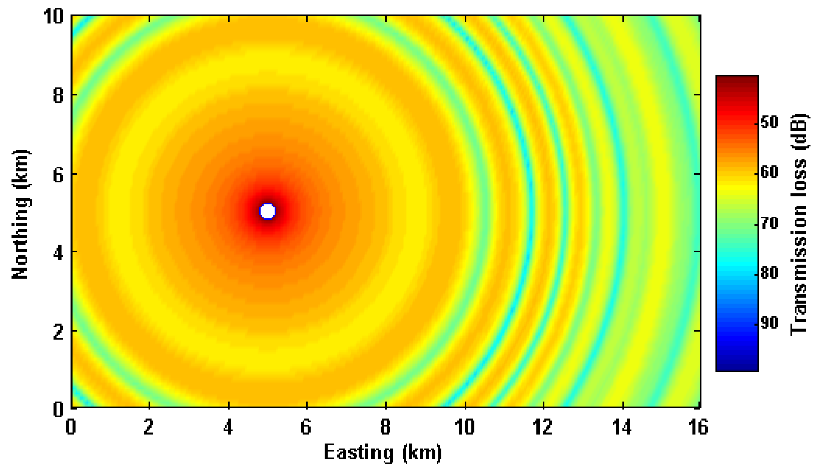


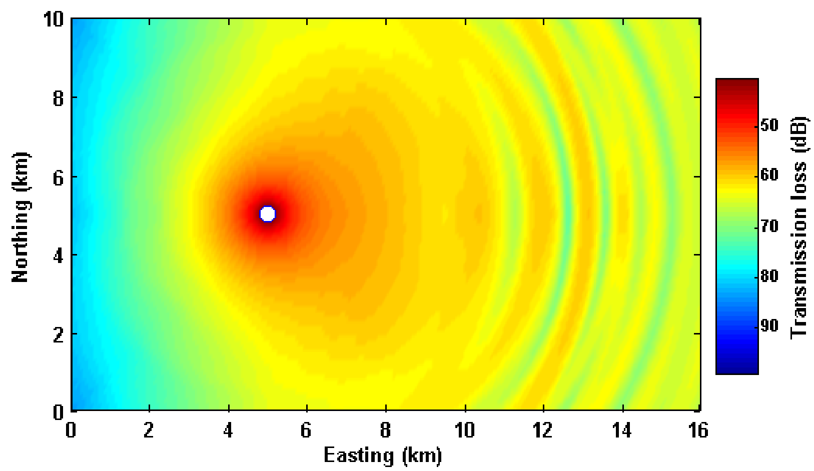
FIG. 12. Sound levels as a function of distance

Again there are essentially no differences in the overall levels, but the differences in the fine detail between the various weather classes are greater at large distances. According to ray theory, this is due to the interference between a large number of sound rays (see Section V below for more discussion).

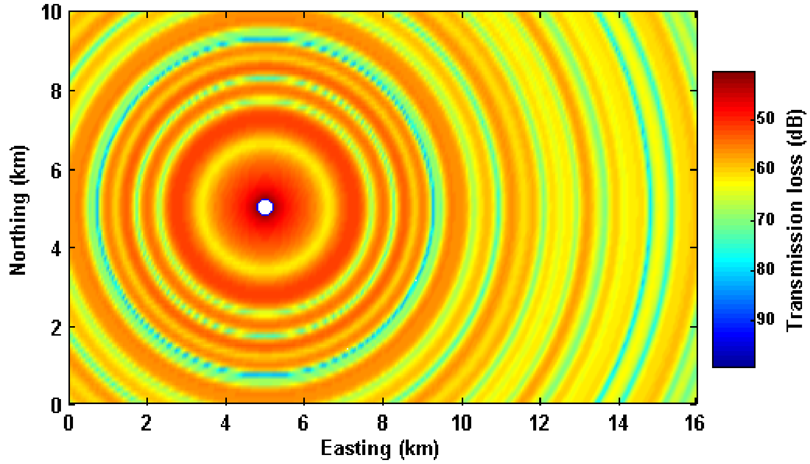
The color plots of the transmission loss for each of the five weather classes are shown below in Figure 13.



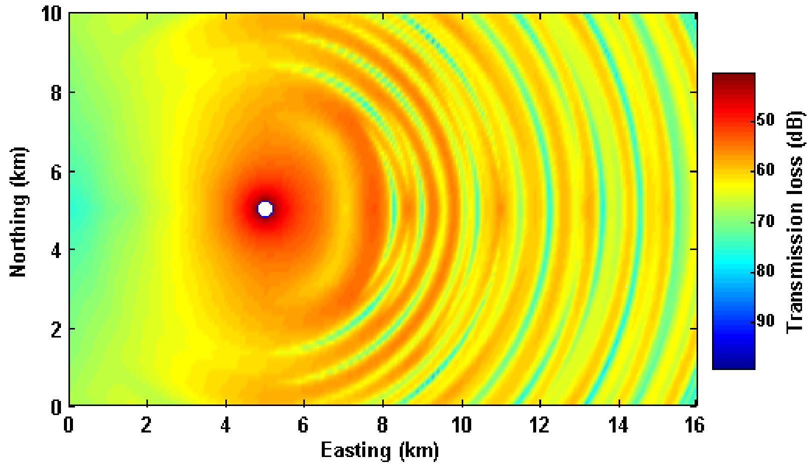
(a) W1/S4



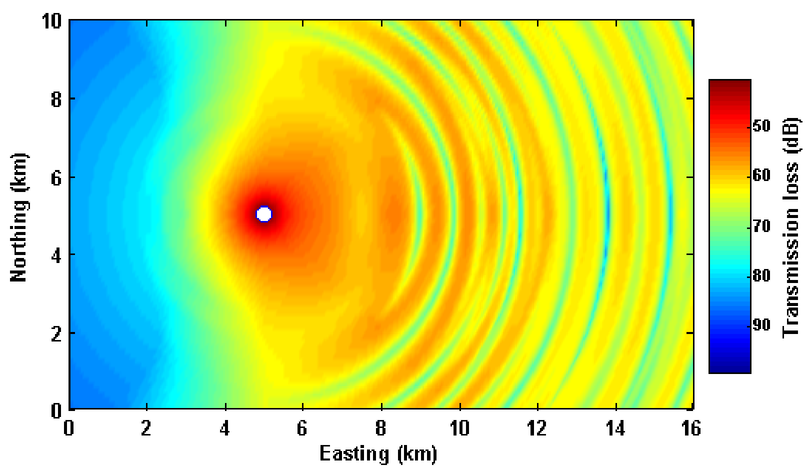
(b) W2/S4



(c) W1/S5



(d) W2/S5



(e) W3/S5

FIG. 13. Color plots of transmission loss

The increasing amount of fine detail, especially east of the source, is clearly evident at the larger distances.

Frequency 6.45 Hz

The sound levels as a function of distance for a frequency of 6.45 Hz are shown below in Figure 14 for the five weather classes.

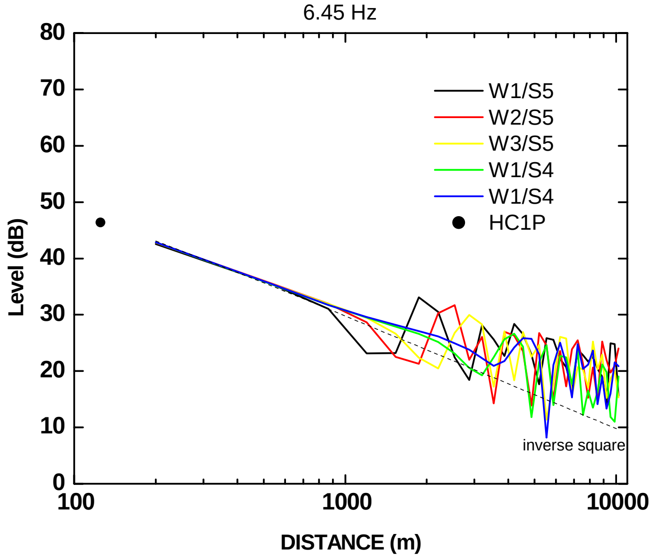
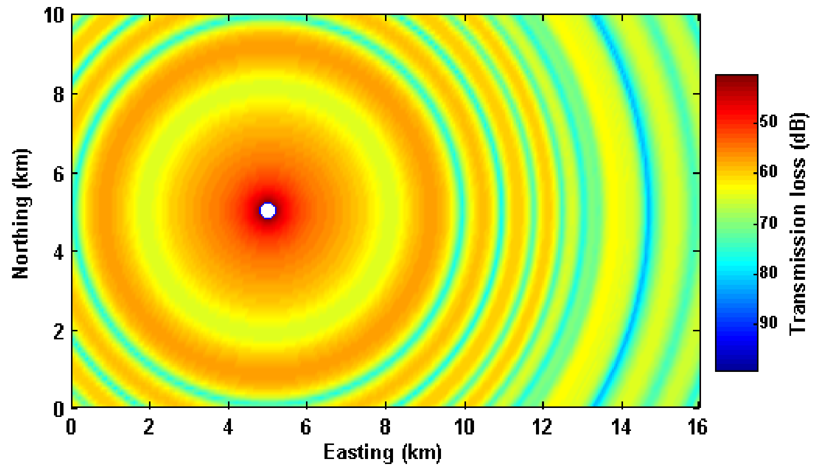


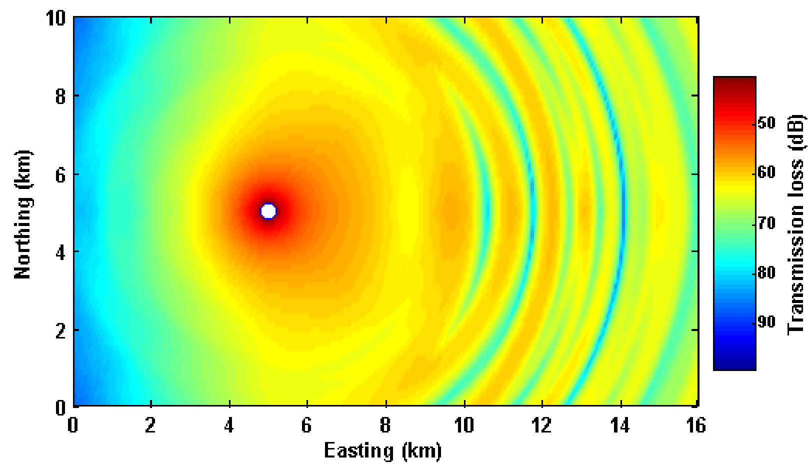
FIG. 14. Sound levels as a function of distance

Again, there are essentially no differences in the overall levels. However, there is more and more fine detail at the large distances.

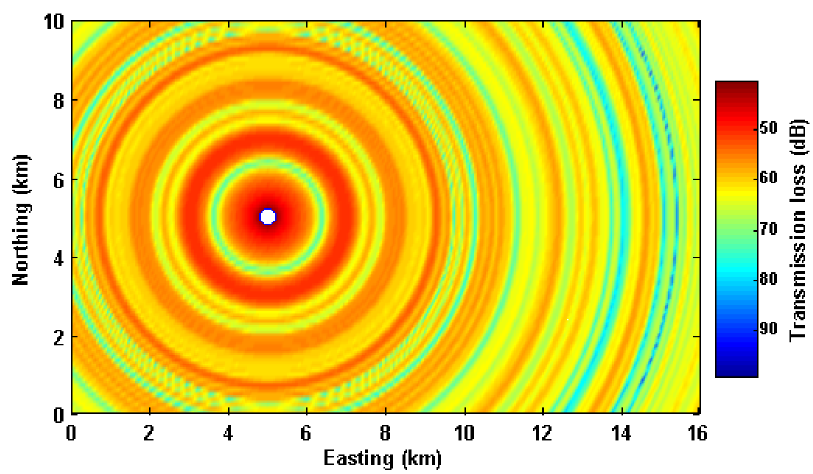
The color plots of the transmission loss for each of the five weather classes are shown below in Figure 15.



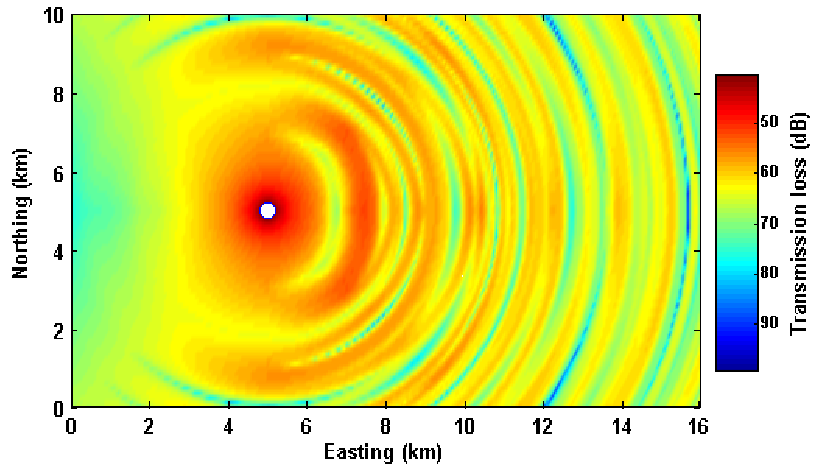
(a) W1/S4



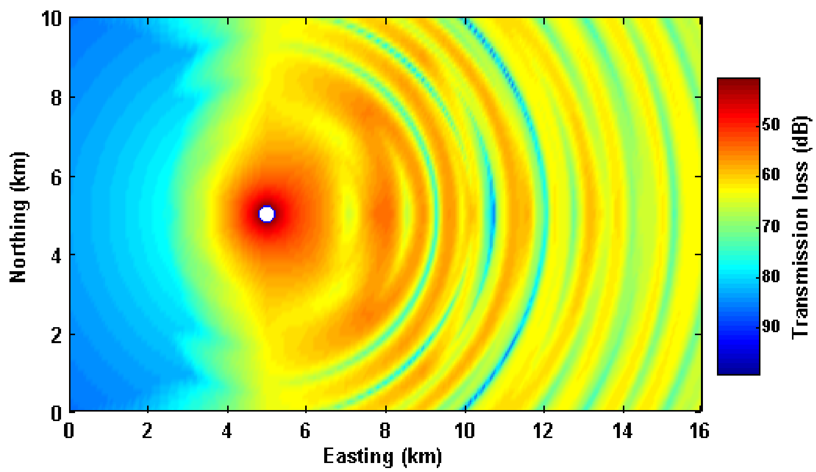
(b) W2/S4



(c) W1/S5



(d) W2/S5



(e) W3/S5

FIG. 15. Color plots of transmission loss

The transmission loss increases very rapidly west of the sound in the case of weather class W3/S5.

Frequency 20 Hz

The sound levels as a function of distance for a frequency of 20 Hz are shown below in Figure 16 for the five weather classes.

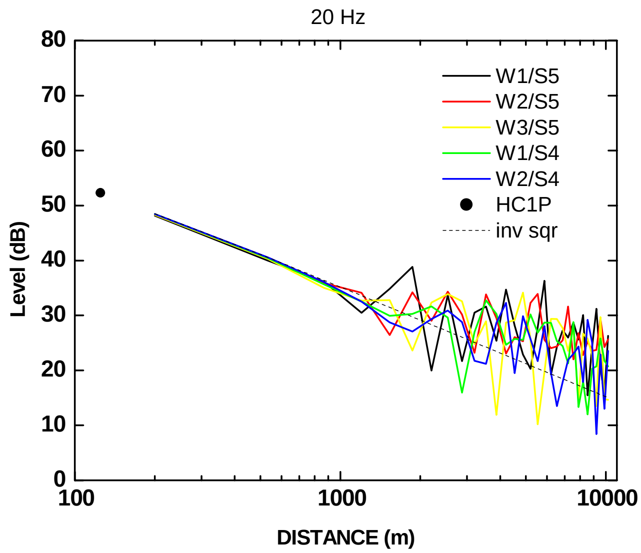
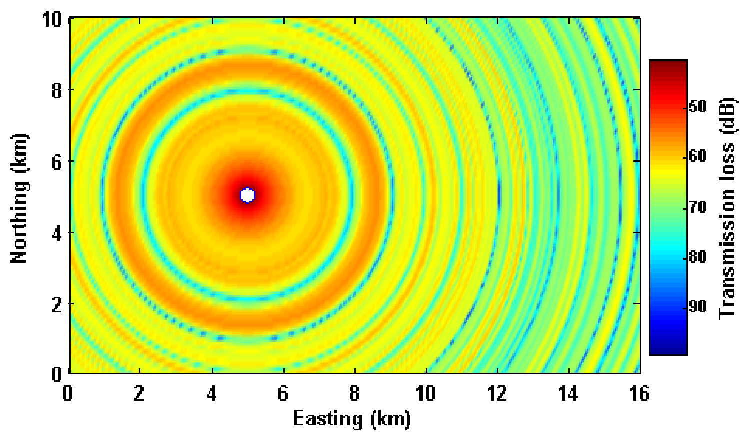
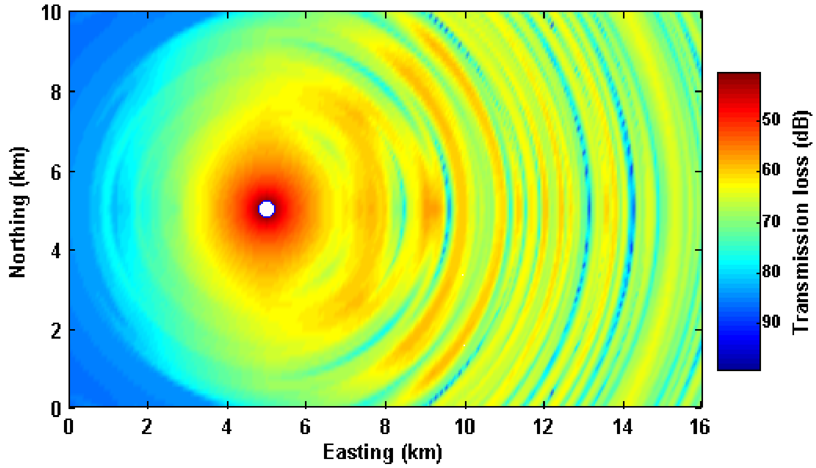


FIG. 16. Sound levels as a function of distance

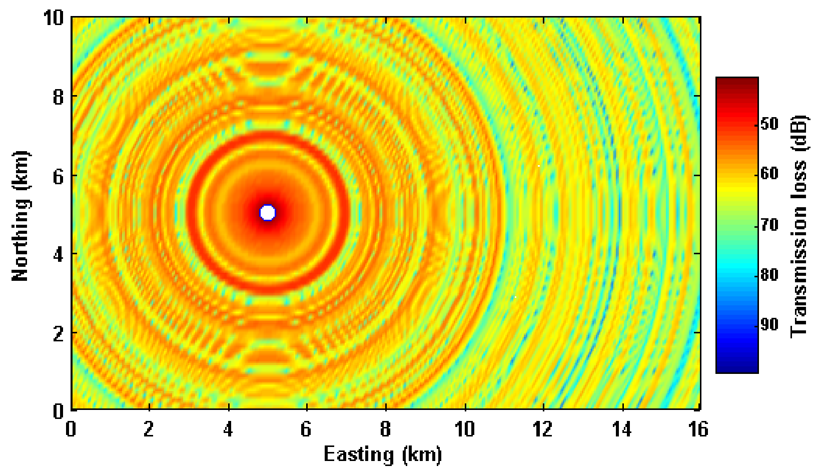
The color plots of the transmission loss for each of the five weather classes are shown below in Figure 17.



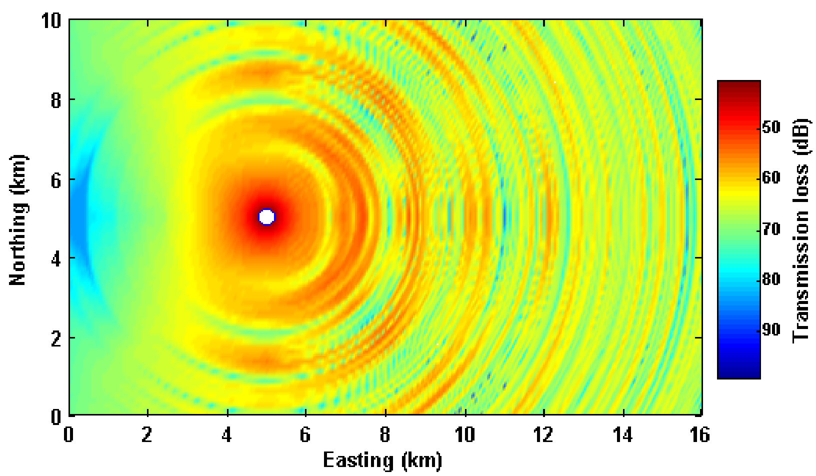
(a) W1/S4



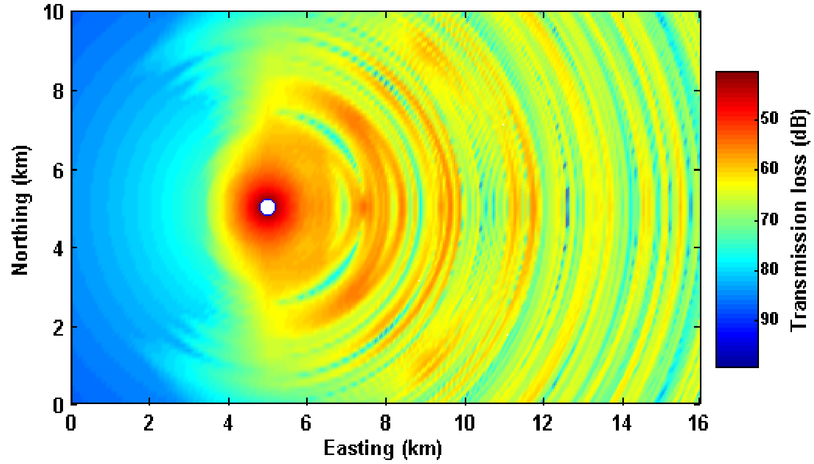
(b) W2/S4



(c) W1/S5



(d) W2/S5

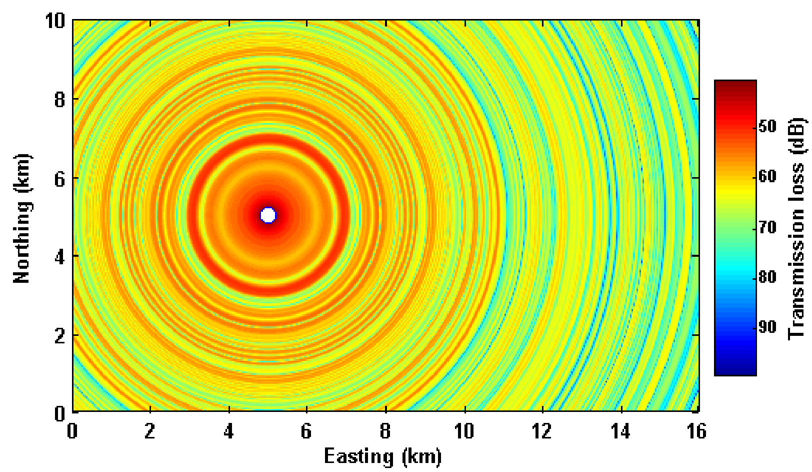


(e) W3/S5

FIG.17. Color plots of transmission loss

Note that minor numerical artifacts have appeared in these color plots, especially for weather class W1/S5 in Figure 17(c). These artifacts result from the finite spatial resolution used for the calculation in order to keep the computation time reasonable for a 10 km × 16 km grid.

If the spatial resolution is increased, the transmission loss shown below in Figure 18 is obtained for weather class W1/S5



W1/S5 high resolution

FIG. 18. High resolution color plot of transmission loss for weather class W1/S5.

The minor numerical artifacts shown in the color plots of Figure 17 do not change the levels shown in Figure 16.

Frequency 45 Hz

The sound levels as a function of distance for a frequency of 45 Hz are shown below in Figure 19 for the five weather classes.

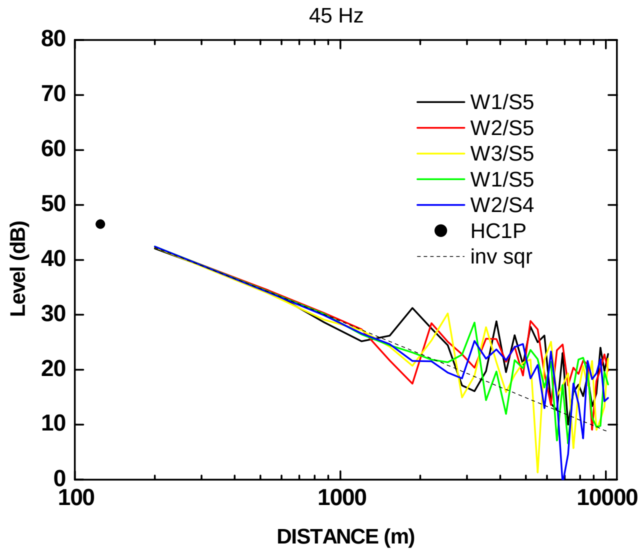


FIG. 19. Sound levels as a function of distance

The ever increasing amount of fine detail at the large distance can be observed. In Figure 20 below, a 10 point adjacent averaging has been applied to the results in the case of weather class W1/S5 (strongest downward refraction) and weather class W2/S4 (least downward refraction) in order to smooth the results.

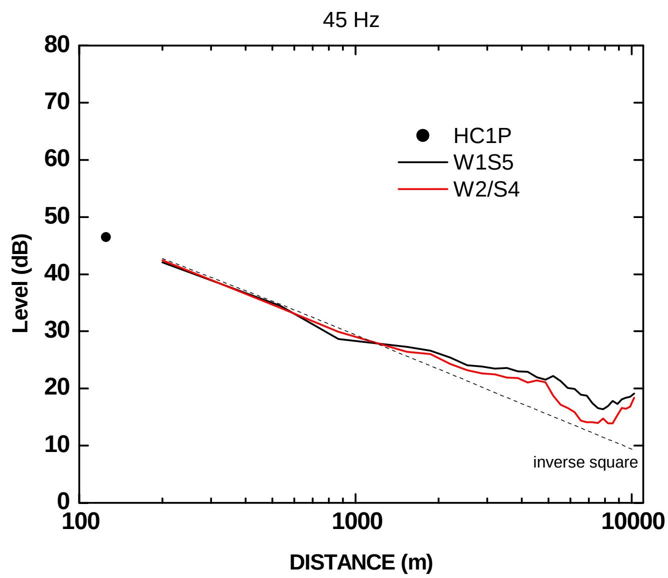


FIG. 20. Smoothing of the sound levels

We note that the levels are marginally higher in the case of weather class W1/S5 at the larger distances.

The transmission loss color plots are very similar to those obtained at 20 Hz and are therefore not show here.

Frequency 70 Hz

The sound levels as a function of distance for a frequency of 70 Hz are shown below in Figure 21 for the five weather classes.

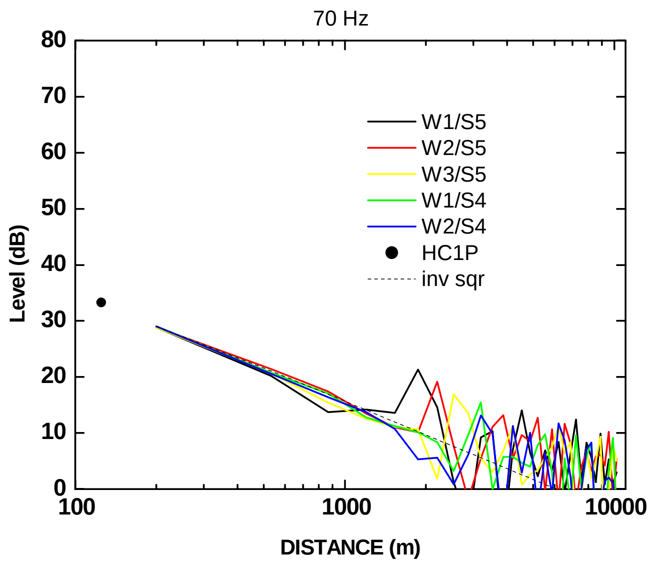


FIG. 21. Sound levels as a function of distance

The amount of fine structure at the larger distances is comparable to the structure obtained at 45 and 20 Hz.

The color plots of the transmission loss is very similar to those obtained at 20 Hz and are not shown here.

V. DISCUSSION

There are a number of cautionary points that are worth emphasizing further. Some of these points were made in the Phase 1 report, but will be repeated here for completeness.

The sound levels and transmission losses calculated for the various weather classes in Figures 8 to 21 are the levels and losses expected from a wind turbine only if the individual weather classes are a reasonable representation of the prevailing meteorology. Often the prevailing meteorology is more complex. Further, profiles generated for Environment Canada data can differ for the profiles generated using local meteorological measurements.

For example, Figure 22 (taken from the Phase 1 report) compares sound levels predicted using data from an on site weather station with sound levels predicted using data from Environmental Canada. The curve labeled "similarity" was obtained using similarity theory and the data collected at the HC2P site in PEI on 14 July 2013). The curve labeled "stability" assumed a profile obtained from Environment Canada observations. The differences in levels are significant at the larger distances.

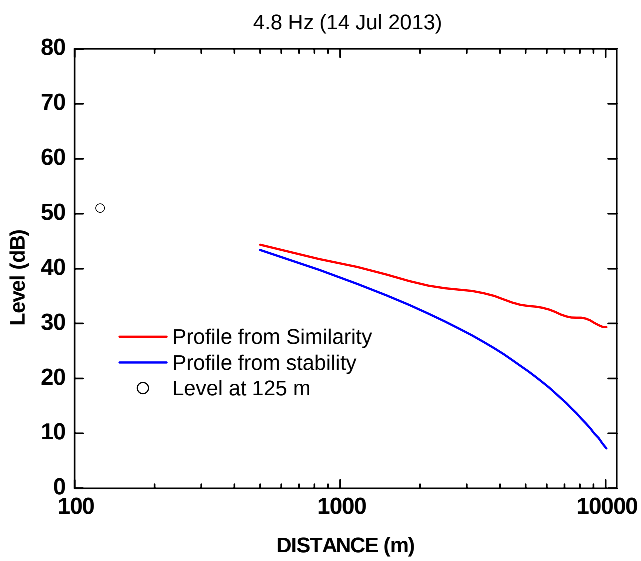


FIG. 22. Sound levels predicted using a dedicated on site weather station compared to sound levels predicted using Environment Canada data

Further, it must be stressed that profiles obtained form similarity theory and stability classes are only valid up to heights of 100 to 200 m. Above these heights, the predicted profiles often become unrealistic. For example, the temperature profile shown in Figure 5 for weather class W1/S5 predicts temperature that reach 300°C at a height of 1 km. This is totally unrealistic.

As general rule of thumb, the sound speed profile must be known to about 1/10 the propagation distance. This generally limits the prediction of sound levels at distances greater than about 1 to 2 km using the profiles obtained from similarity equations or the stability classes.

Nonetheless, we were able to obtain reasonable agreement between predicted and measured levels at the PEI site up to distances of 10 km for a variety of cases. We reproduce a ray picture from the Phase 1 report obtained from the profiles predicted from similarity scaling and data measured on 11 June 2013 at site HC2P. The sound speed profile is very close to the profile obtained from weather class W1/S4. The rays show that most of acoustic energy is focused at heights below 200 m and we speculated that this was most likely the reason for the agreement between predicted and measured levels for the cases considered. However this may not be generally true. For larger propagation distances (> 2 km), it is best to use data obtained locally from weather balloons, sodar, etc.

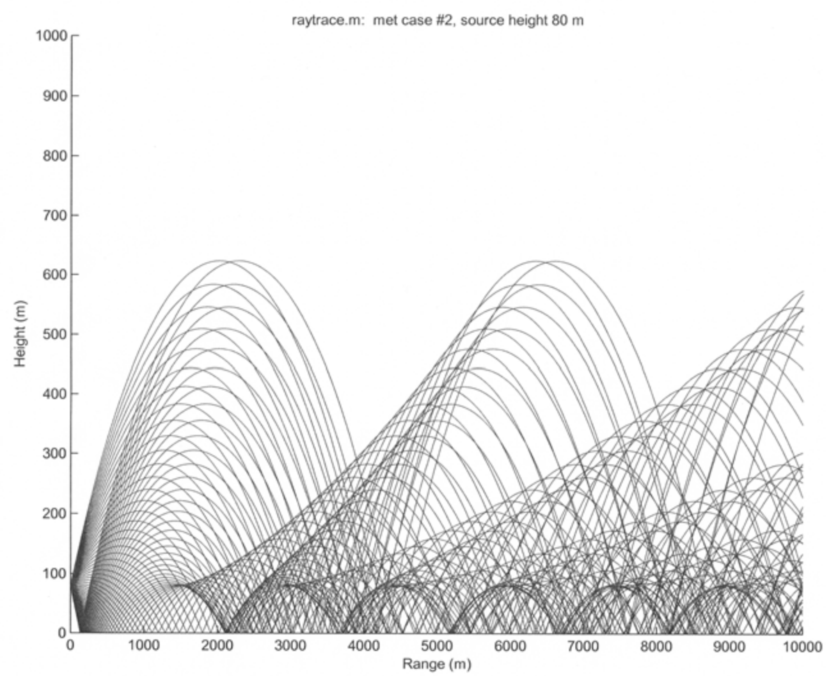


FIG. 23. Sound rays during inversion conditions

In Section IV.B., we remarked on the fine detail that is observed in the predicted levels at the larger distances. The fine detail is explained according the ray theory by the interference between the various rays illustrated in Figure 23. The FFP that we are using for this report is a full wave analysis that inherently handles the complexities of the sound field illustrated by the ray picture in Figure 23. It is unlikely that this fine detail could be systematically resolved experimentally. However, it does explain the spread in measured levels on different days during similar weather conditions. To illustrate this point the levels predicted for a frequency of 3.22 Hz for the five weather class from Figure 10 are reproduced in Figure 24 below. The open points are measured levels obtained on PEI during various inversion conditions between June and September 2013.

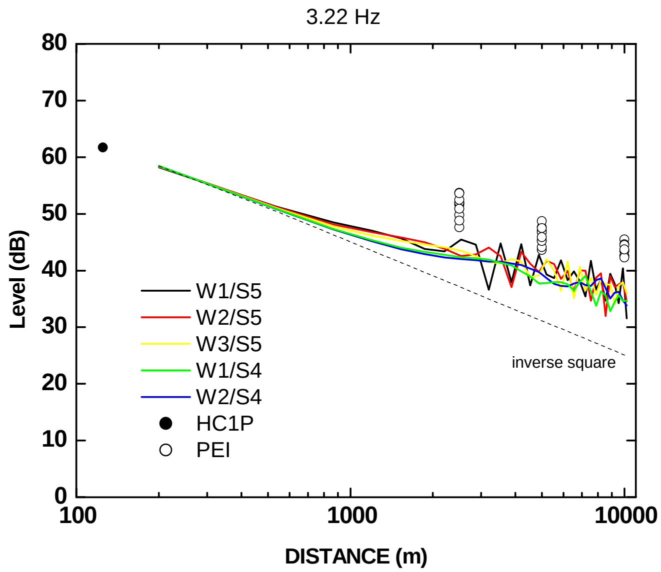


FIG. 24. Predicted levels from Figure 10 and data from PEI

The spread in the measured levels at each distances is comparable to the differences in the detail between the various inversion weather classes.

Recall that the predicted levels in Figure 24 are for one turbine, but the measured levels on PEI are the sum from four turbines – because of this, the PEI data would be expected to lie approximately 6 dB above the calculated curves.

VI. CONCLUDING REMARKS

If commercial software is going to be used to predict infrasound propagation then it is imperative that their low-frequency predictions be validated against calculations using either the PE or FFP methods. In this report, the FFP method was used to generate propagation results for a well-defined generic test site under specific meteorological conditions. This will permit Health Canada to perform comparable calculations using their commercial software and, hence, enable a comparison.

It was agreed that MG Acoustics would perform calculations for the “worst case” meteorological situations (i.e. conditions that are expected to lead to highest sound levels) and for frequencies below 100 Hz and down to the infrasonic frequencies. These “worst case” meteorological conditions occur during inversion or inversion plus downwind propagation conditions and correspond to weather classes W1/S4, W2/S4, W3/S4, W1/S5, W2/S5, W3/S5 and W4/S5.

Note that these seven weather classes occurred about 45% of the time (or 3942 hours out of 8760 hours) in 2013 in the [redacted] area. However, a statistical analysis of levels around a wind turbine farm must also take the prevailing wind direction into account.

During the summer, farm land will be covered with crops or tall grass. During a good part of the spring and fall, large portions of farm land will be uncultivated. During the winter, the ground will be frozen or partially frozen and often covered with a layer of snow. The snow cover can range from fresh snow to wind swept mature snow and also includes wet granular snow and ground only partially covered with snow (dry, wet or ice covered).

The calculations revealed that only a fresh cover or a mature never-melted snow cover produced lower sound levels at the larger distance. For all other ground cover, the calculated levels were essentially the same.

The calculations also revealed that the average levels for each frequency were comparable at the larger distance for all seven weather classes considered. There are systematic differences in the fine detail due to the interference between the large number of rays present during downward refraction. It is unlikely that this fine detail could be systematically resolved experimentally. However, fluctuations in levels are always observed during outdoor measurements. Variation in the fine detail over time also explains the spread in the measured levels shown in the Phase 1 report during the various inversion conditions between June and September.

Finally, it must be cautioned that the profiles generated from the stability classes are generally only valid up to heights of 100 to 200 m. On other hand, reliable prediction sound levels at larger distances (> 2 km) generally requires profiles up to about 1 km. For larger distances it is best to use meteorological data obtained from weather balloons, sodar, etc.

VII. REFERENCES

R. Eurasto (2006), "Nord2000 for road traffic noise prediction. Weather classes and statistics", Research Report VTT-R-02530-06, VTT Technical Research Centre of Finland.