6th International Meeting
on
Wind Turbine Noise
Glasgow 20-13 April 2015

Sensitivity analysis test on the Italian ISPRA-ARPAT methodology to assess noise impact of operational wind farms.

Luca Fredianelli. Department of Physics - University of Pisa, Largo B. Pontecorvo, 3 - 56127 Pisa, Italy.
E-mail: fredianelli@df.unipi.it

Paolo Gallo. Environmental Protection Agency of Tuscany Region
Via N.Porpora, 22 – 50144 Firenze, Italy.
E-mail: p.gallo@arpat.toscana.it

Gaetano Licitra. IPCF-CNR Uos, Via G. Moruzzi 1, 56124 Pisa, Italy
E-mail: g.licitra@ipcf.cnr.it

Diego Palazzuoli. Environmental Protection Agency of Tuscany Region
Via N.Porpora, 22 – 50144 Firenze, Italy.
E-mail: d.palazzuoli@arpat.toscana.it

Stefano Carpita. Department of Physics - University of Pisa, Largo B. Pontecorvo, 3 - 56127 Pisa, Italy.
E-mail: carpitastefano@gmail.com

Summary

In 2013 the Italian Institute for Environmental Protection and Research (ISPRA), in cooperation with the Environmental Protection Agency of Tuscany Region (ARPAT), published a new methodology for the assessment of noise impact of operational wind farms.
By means of measurement campaigns of specific noise and weather parameters at the receivers lasting at least 3 weeks, the procedure simultaneously provides an estimation of noise emission and prevailing background noise, also if the main component of the latter is due to wind.
Through iterative steps, the method provides the evaluation of noise impact produced by operational wind farms, without stopping them for measurement purpose. Moreover, the algorithm implemented involves the use of some specific numerical values to be assigned to the parameters for the calculation of noise propagation.
The method has been successfully tested through specific measurement campaigns in nearly ten Italian sites with different orography conditions, but a proper uncertainty analysis has not been performed yet.
The paper presents some preliminary results of the sensitivity analysis of the new methodology, aiming to establish the influence that a variation of a specific input of the procedure has on the outcome.

This will allow a better understanding of which assumptions are critical and which parameters require more accuracy in the acquisition step. This analysis also provides a confidence level for the outputs and defines an empirical approach to determine an estimation of their uncertainty.

1. Introduction

Wind Turbine Noise (WTN) presents particular aspects that distinguish it from the other industrial noise sources: the most important of these aspects is the increase in the overall noise level due to the constant presence of wind during measurements at the receivers. Also wind turbulence on the microphone surface [1], residual noise from other nearby sources, background noise produced by the interaction of wind with the surrounding environment [2,3], are all effects very hard to select and add to the noise emission from wind turbines.
Both emission and residual components of measured noise levels (prevailing background) are strongly dependent on wind speed [4], so it is very difficult to estimate their specific contribution from the overall result of a measurement performed when the plant is operational. In some Countries, this is necessary for the assessment of the compliance with regulatory limits [9], but generally all the procedures require the plant to be temporarily shut down in order to measure the residual noise. This operation has a big economic impact on the wind farm managers. An additional problem is that wind speed and direction, at ground level, are affected by time and space variation, particularly in complex terrain [5]. A measurement of residual noise can lead to an incorrect noise evaluation if it is performed: a) in a time period different from that of measurement of the environmental one; b) simultaneously to environmental noise measurement, but in a site far from the receiver.
In 2013 the Italian Institute for Environmental Protection and Research (ISPRA) published a new methodology for the assessment of WTN, solving the issues mentioned above.
The procedure is able to simultaneously estimate the emission and residual components of the noise levels measured nearby a wind farm by means of a measurement campaign of specific noise and weather parameters at the receiver lasting at least 3 weeks. Through iterative steps, the method provides the evaluation of noise impact produced by operational wind farms, without stopping the farm for measuring the residual background noise. The method have been successfully tested through specific measurement campaigns in some Italian sites with different orography conditions, but a proper uncertainty analysis has not been performed yet.
In this paper the estimation of the coverage interval associated with the output noise levels from the ISPRA-ARPAT procedure is performed through a Monte Carlo procedure.

2. The ISPRA-ARPAT procedure

ISPRA procedure [6] considers the residual noise levels as a function of wind speed at ground and the emission levels at receivers as a function of a new parameter, the equivalent blades rotational speed $N_{eq,tot}$. Both are computed through appropriate iterative phases and energetic subtraction between measured noise levels grouped in classes of wind speed at ground and blades rotational speed. The procedure is applicable to data from outdoor measurements and allows different calculation for day-time and night-time, flat terrain and complex terrain.

2.1 Data acquisition

For each receiver, ISPRA-ARPAT procedure needs the following set of data acquired over 10' for at least 2000 measurement intervals, that correspond to nearly 2 weeks of continuous measurements. For each ten minutes the data required are:
a) Acoustic data:
- $L_{Aeq,10'}$ evaluated on successive time intervals of 10';
b) Meteorological data:
- Average wind speed at ground (at a height of 3 m above ground);
- Precipitation (rain, snow, hail);
- Most frequent wind direction at each turbine rotor;
- "N": the average blades rotational speed (in round per minutes [rpm]) for each turbine with a distance receivers-blade less than or equal to 1 km;
The measurements have to be performed outdoor near the building receiver, with the microphone placed at 1 m away from the façade, at least 5 m away from other reflective surfaces, trees or possible interfering sources and at 4 m above the ground. The weather station should be placed at 3 m above the ground as close as possible to the microphone, but always at least 5 m from interfering elements capable of producing turbulence and in such a position that it can receive wind from all directions.

2.2 Database creation

All the data acquired as described in 2.1 are necessary to build a database, where the rows are the 10' intervals and at each row corresponds column with all requested parameter for that interval. For each ten minute data, the value $N_{eq,i}$ have to be computed for each wind turbine. It represent a virtual rotational speed which would have the i-th wind turbine to produce the same noise levels measured at the receiver if the i-th wind turbine were in the same position as the one closest to the receiver. This value is calculated weighting the measured rotational speed with suitable parameters according to the ISO 9613-2 [7] propagation, including: distance and direction between wind turbines, wind direction, ground type, period of the day and atmospheric attenuation. For each 10', a single value for rotational speed is calculated, the $N_{eq,tot}$, corresponding to the virtual rotation of all the wind farm in that 10' period.
In its final form, each row of the data array should display the values of $L_{Aeq,10'}$, wind speed at ground (v_{gr}) and $N_{eq,tot}$ correspondingly to each consecutive time interval of 10'. The values of v_{gr} and $N_{eq,tot}$ are approximated to the nearest integer, whereas the $L_{Aeq,10'}$ values to 0,5 dB(A).

2.3 Iterations and outputs

The procedure consists in 3 different steps:

1. A first calculation of the residual noise, not dependent on v_{gr};
2. An estimation of the noise emission at receiver of the whole wind farm as a function of $N_{eq,tot}$;
3. An estimation of the residual noise as a function of v_{gr}.

At *Point 1* an initial residual noise level is obtained with a $N_{eq,tot}$ threshold, for which $N_{eq,tot}$ value below that threshold can be considered as not relevant for noise impact on the receiver. The residual noise level have a wind speed dependence.

At *Point 2 and* 3, noise levels are respectively classified for finite interval of $N_{eq,tot}$ and v_{gr}. To calculate the noise emission as a function of $N_{eq,tot}$, the residual level as a function of v_{gr} is energetically subtracted to the measured noise, then a best fit is produced. This fitted relation is energetically subtracted to measured noise to obtain a residual noise as a function of wind speed at ground. Again a best fit of this relation is produced. *Point 2* and *Point 3* are strictly connected and based one on another. In fact, once a first estimation of the noise emission is obtained, it is used to calculate a better estimation of the residual noise and vice-versa. This iteration of energetic subtraction of the fitted relations continue until no new information are added between the one iteration and the following.
The outputs of the procedure are noise emission levels at receiver as a function of $N_{eq,tot}$, residual noise at receiver as a function of v_{gr} and the total emission and residual noise at receiver (i.e. the equivalent mean levels evaluated on the measurement period distinguishing between night time and daytime) that is computed weighting the noise levels in each classes with the corresponding occurrences. Figure 1 is a summary diagram of the procedure.

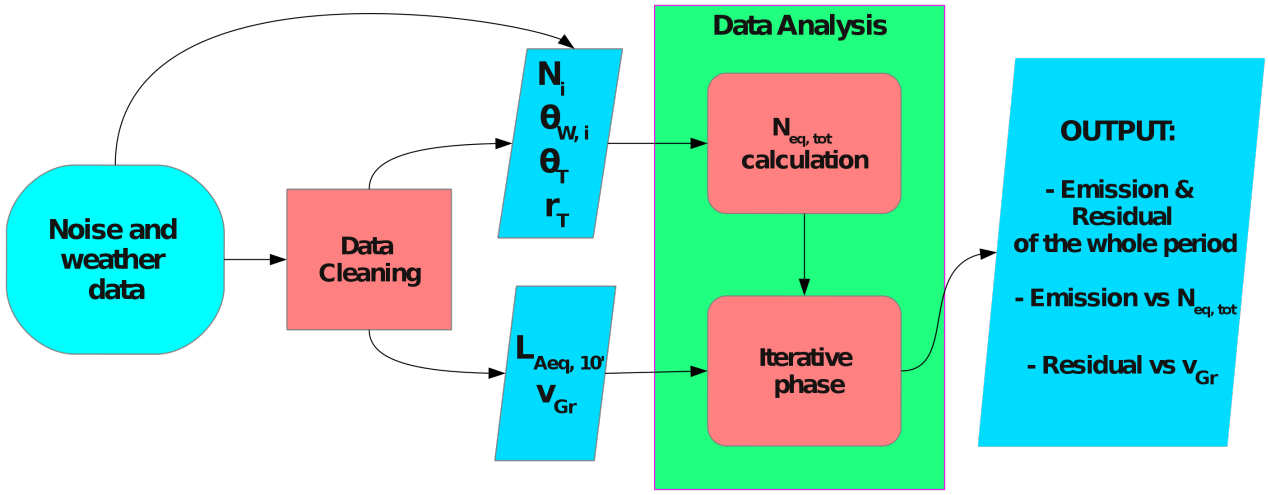

Figure 1: summary diagram of the ISPRA-ARPAT procedure.

3. Monte Carlo uncertainty analysis

The uncertainty analysis with a Monte Carlo method (MCM) was performed using the adaptive procedure presented in the Guide to the expression of uncertainty in measurement (GUM) [8]. The MCM basically consists in propagating the distributions of the inputs through the model to obtain a consequent distribution of the outputs. MCM can be summed up in the following steps:

1. set up of a probability distribution function (PDF) for every input;
2. pseudo-random numbers sampling from the PDFs;
3. computation of the model for every sampled value;
4. assemblage of the distribution function for the outputs (G);
5. calculation of uncertainty on the outputs from the standard deviations of the Gs.

The convergence of MCM is assured increasing the number of iterations until the stabilisation of the statistical parameters as defined by GUM [8].
The $N_{eq,tot}$ parameter has a key role in the ISPRA-ARPAT procedure, an estimation of its uncertainty is preliminary to the uncertainty analysis of the iterative phase of the procedure.
The procedure and the Monte Carlo Method was implemented in R Free Software programming language. [14]

3.1 Testing Sites

The ISPRA-ARPAT procedure has been tested with data from six different wind farms, reported in Table 1. Figure 2 shows the distribution of the turbines around each receiver.

Wind farm	Turbines considered	Number of 10' data
La miniera-Scapiccioli	4	1725
La miniera- Provinca	4	1287
Poggi alti-Scansano	7	1297
Lucera	3	997
Riparbella	6	1384
Santa luce	5	2209

Table 1: information about test sites.

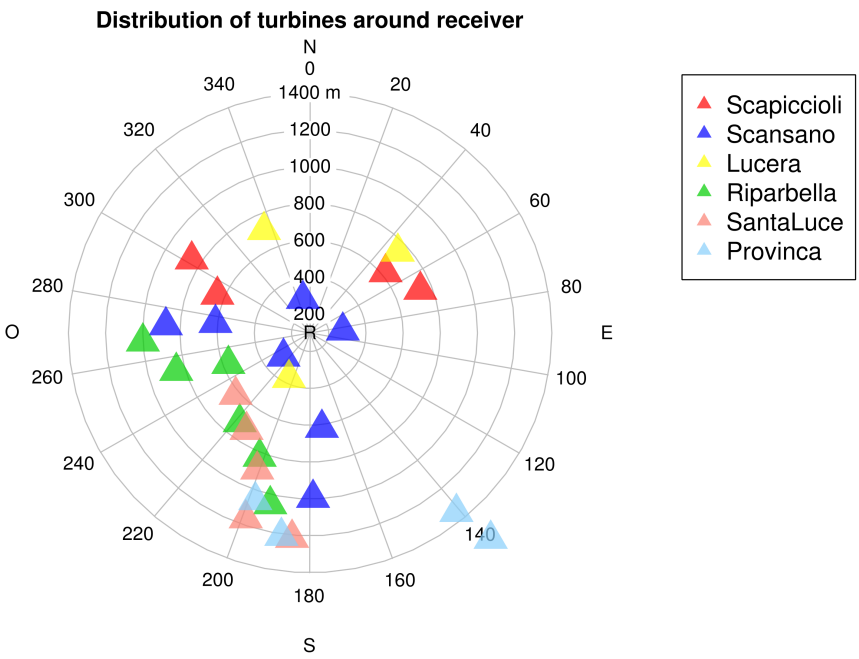

Figure 2: distribution of wind turbine around receiver in the test sites.

3.2 Uncertainty of $N_{eq,tot}$ parameter

$N_{eq,tot}$ is a parameter calculated for each 10' interval considering the N_i, weather and plant measured data and two fixed parameters. These parameters concern the environment surrounding the receivers and in this paper they are assumed without uncertainties. The measured input data, along with their PDF and available measurement uncertainties, are reported in Table 2.

Inputs	PDF	Parameters
N [r.p.m.] *blades rotational speed*	rectangular	Half width=0.5
Θ_W [deg] *wind direction from North*	Gaussian	σ= 3
Θ_T [deg] *directions turbine-receiver from North*	rectangular	Half width=1
r_T [m] *distances turbine-receiver*	rectangular	Half width= r_T *0.03

Table 2: input data with probability density function for the calculation of $uN_{eq,tot}$.

The Neq,tot uncertainty has been estimated for each 10' data using the sigma of the Gaussian PDF that fits the obtained MCM numerical distribution. In Figure 3 two examples are reported for a single Neq,tot. The uncertainties for each Neq,tot in each test sites have been reported on a graph in Figure 4.

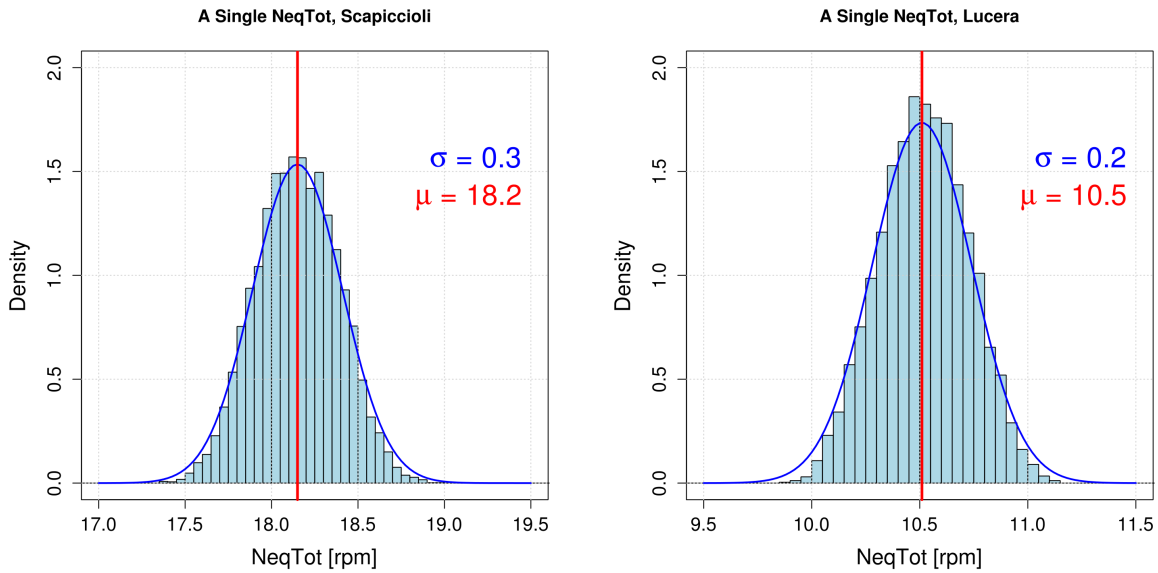

Figure 3: uncertainty of a single $N_{eq,tot}$ for two test sites.

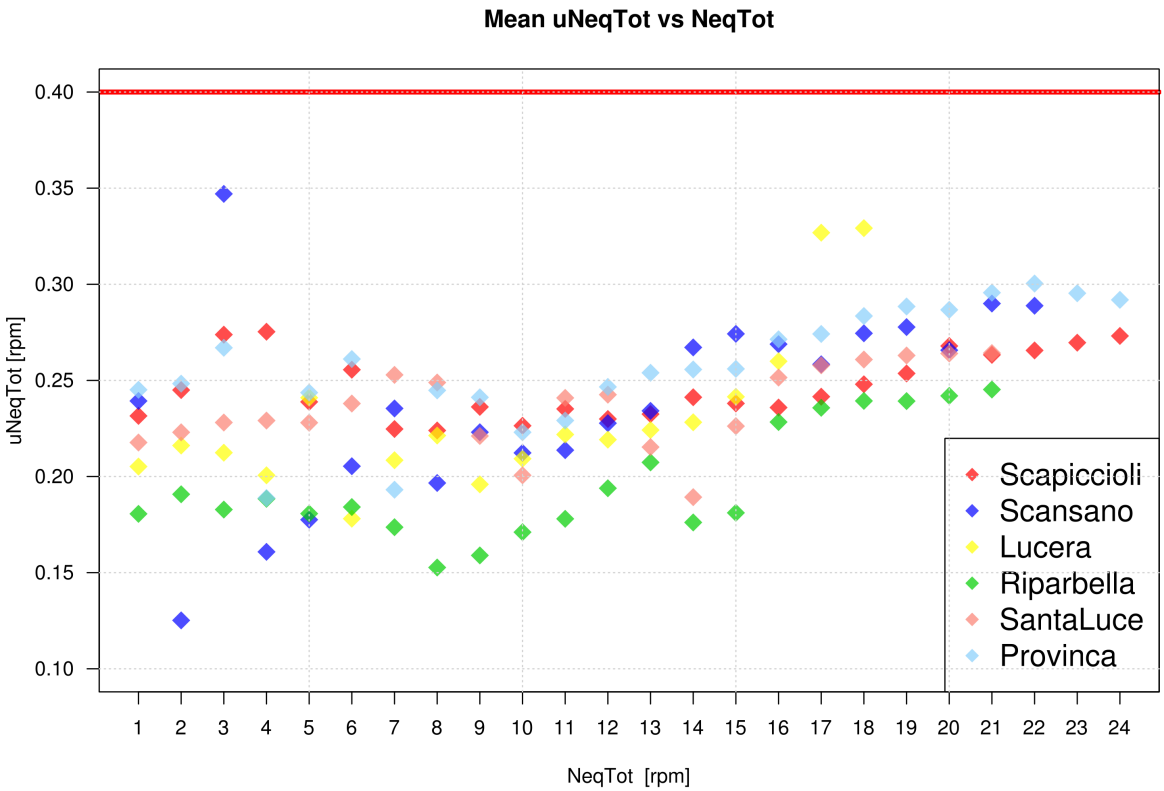

Figure 4: uncertainty for each $N_{eq,tot}$ for all the test sites.

The uncertainties on the singles $N_{eq,tot}$ result lesser than 0.4 rpm for every test site and every $N_{eq,tot}$ value. This value is assumed as the $N_{eq,tot}$ uncertainty ($uN_{eq,tot}$) and it results comparable with the uncertainty on the input measured rotational speed N.

$$\mathbf{uN_{eq,tot} = 0.4}\ [\text{rpm}]$$

3.3 Coverage interval of the procedure

In this section are analysed the uncertainties of the outputs in the procedure by using the MCM over the iterative phase. As already reported, the input variables are the following 10' parameters:

- $L_{Aeq,10'}$, A weighted noise equivalent level over 10';
- v_{gr} , wind speed at ground;
- $N_{eq,tot}$, calculated in the previous step of the procedure.

The inputs of the model are 3 times the number of 10' data. As an example, Scapiccioli test site have 1725 data, so 1725*3 inputs. Each input vary according to the distributions in Table 3.

Parameters	PDF	Uncertainty
$L_{Aeq,10'}$ [dB(A)]	Gaussian	σ= 1.3
v_{gr} [m/s]	rectangular	Half width=0.4
$N_{eq,tot}$ [rpm]	Gaussian	σ= 0.4

Table 3: Input data with probability density function for the calculation of the uncertainties of the procedure.

$L_{Aeq,10'}$ uncertainty has been evaluated as the root mean square of the type B uncertainties:

- u_{str}= 0.5 dB(A), instrumental uncertainty;
- u_{cond}=0.2 dB(A), measurement conditions uncertainty;
- u_{meteo}= 1.2 dB(A). meteorological conditions uncertainty.

These values have been evaluated following prescriptions of GUM [9], UNI ISO 1996-2/2007 [10], UNI/TR 11326 [11]. Uncertainty associated to v_{gr} is the measurement ones, while the $N_{eq,tot}$ uncertainty was previously calculated.

In Table 4 are reported the day average noise emission and residual calculated with Monte Carlo procedure and their respective coverage interval (CI).

Test site	Emission [dB(A)]	CI (95%) [dB(A)]	Residual [dB(A)]	CI (95%) [dB(A)]
Scapiccioli	40.3	2.2	38.4	1.6
Scansano	45.7	2.4	43.6	1.8
Lucera	43.4	2.6	40.5	1.6
Riparbella	41.6	2.0	40.6	1.2
Santa Luce	38.4	1.2	33.5	1.6
Provinca	36.5	2.0	35.7	1.4

Table 4: Emission and Residual over the whole measurement period and their coverage interval (CI)

In Figure 5 are plotted the output G distributions obtained by MCM. All the G distributions failed most popular normality tests (Chi Squared, Lilliefors, Anderson-Darling, Cramér-Von Mises...). For symmetric Gs coverage intervals have been evaluated by using quantile values from resulting distributions. A 95% coverage interval has been chosen selecting endpoints at $q_{2.5\%}$, $q_{97.5\%}$ quantiles.

$$\mathrm{CI}\ (95\%)=\left(q_{97.5}-q_{2.5}\right)$$

For asymmetric distributions, eg. Scapiccioli and Scansano, coverage interval endpoints have been evaluated by taking the 95% coverage interval (CI) with minimum width according to paragraph 5.3.4 of [8].

The evaluated CIs show some differences from site to site (except the very sharp one at Santa Luce), of about 1.2 dB(A), suggesting a not very strong dependence on measurement conditions and on testing sites.

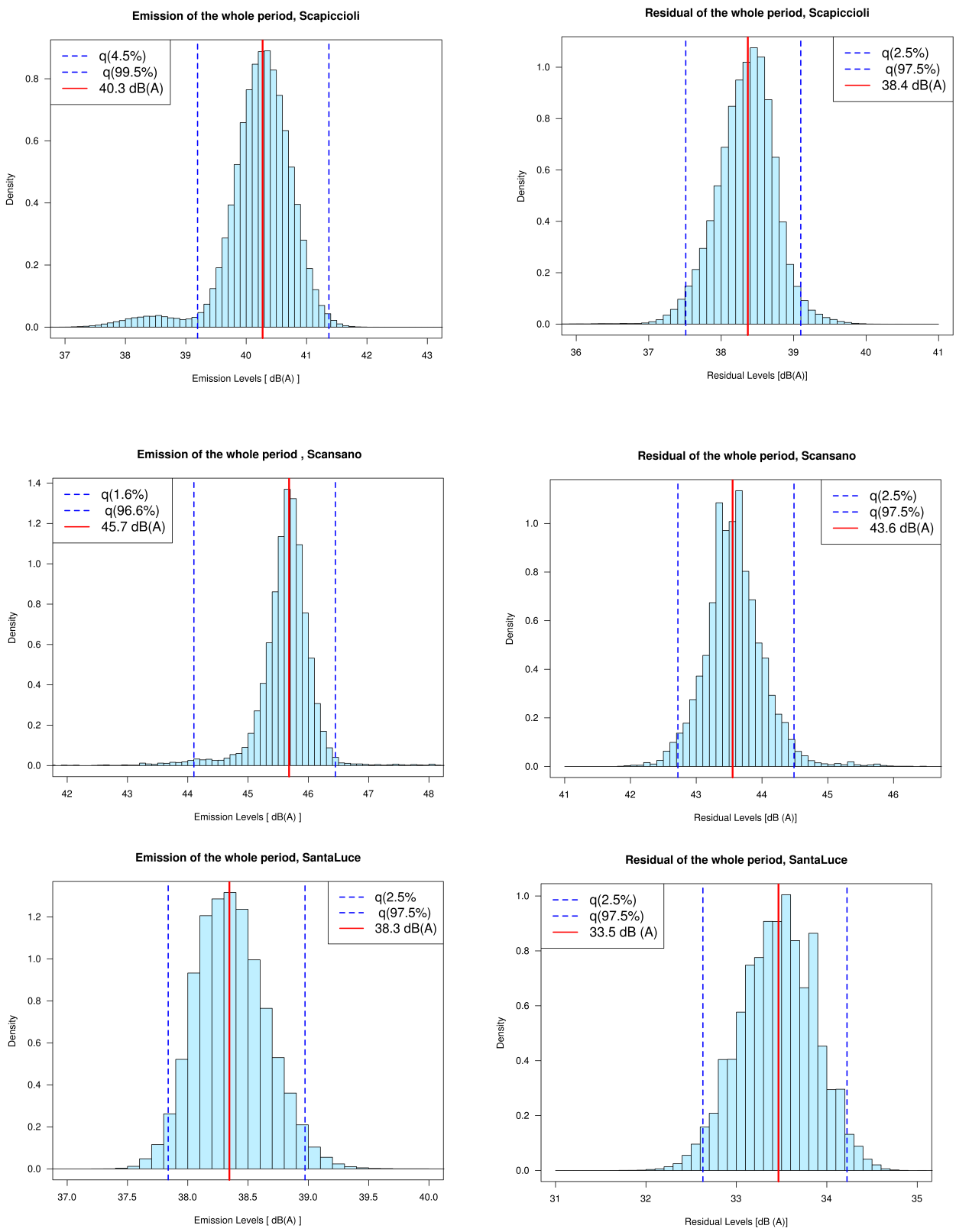

Figure 5: MCM output distributions for Emission ad Residual of some test sites.

3.4 Uncertainties on Emission vs $N_{eq,tot}$ and on residual vs v_{gr}

An intermediate step of the ISPRA-ARPAT procedure allows the evaluation of the emission noise levels as a function of $N_{eq,tot}$, and the residual noise as a function of wind speed at ground. The uncertainties of this part have been evaluated as in previous section for every $N_{eq,tot}$ value. Figure 6 represents the emission vs $N_{eq,tot}$ and the residual vs v_{gr} of all the test sites. Figure 7 shows how uncertainties depends on $N_{eq,tot}$, with minimum values for central $N_{eq,tot}$ range, and higher values at extreme $N_{eq,tot}$ values, for nearly all the testing sites. Figure 8 represents the uncertainties of noise vs v_{gr} .

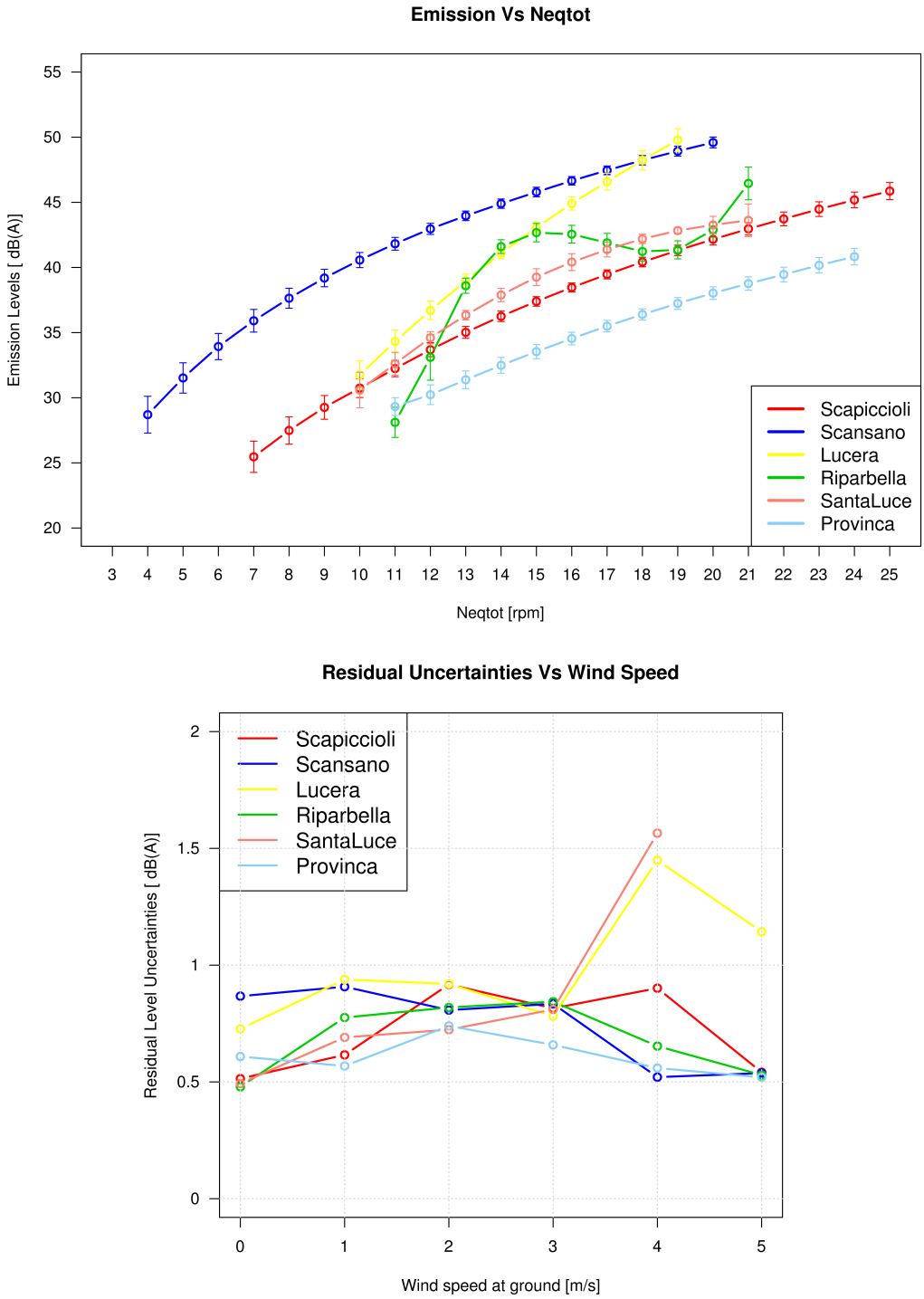

Figure 6: emission vs $N_{eq,tot}$ and the residual vs v_{gr} of all the test sites.

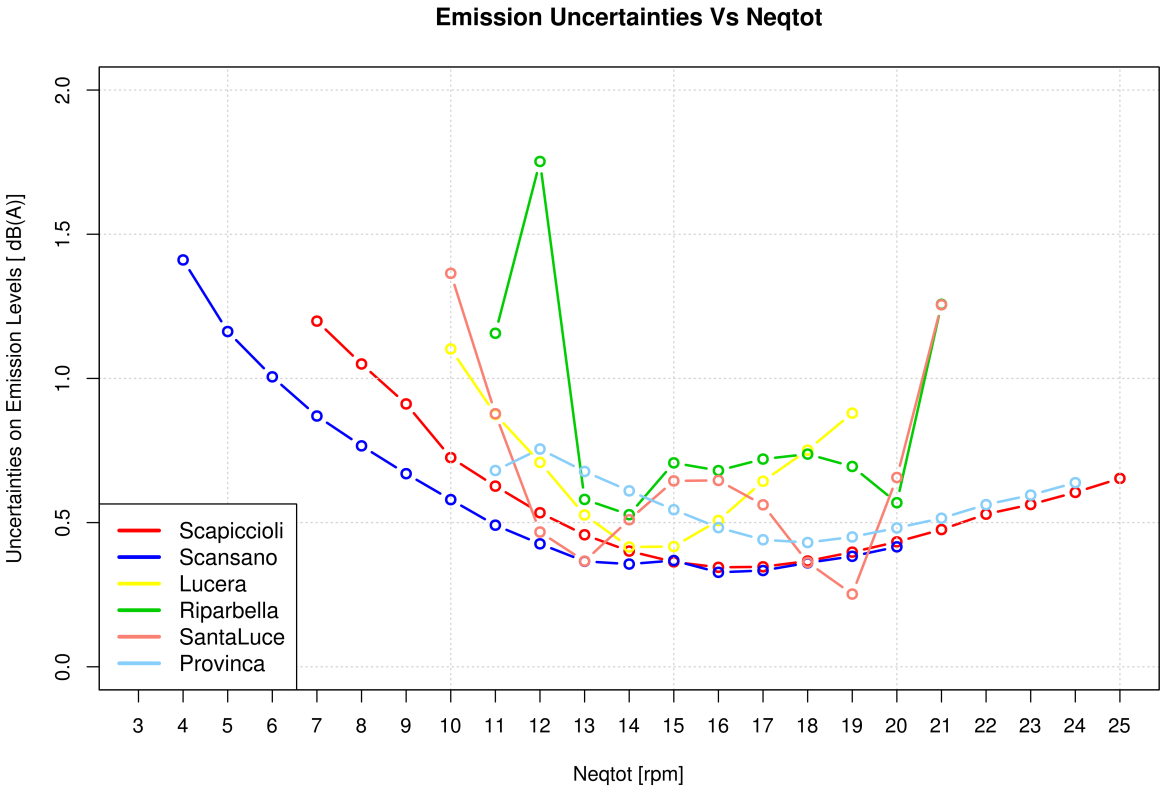

Figure 7: uncertainty on emission vs $N_{eq,tot}$ for all the test sites.

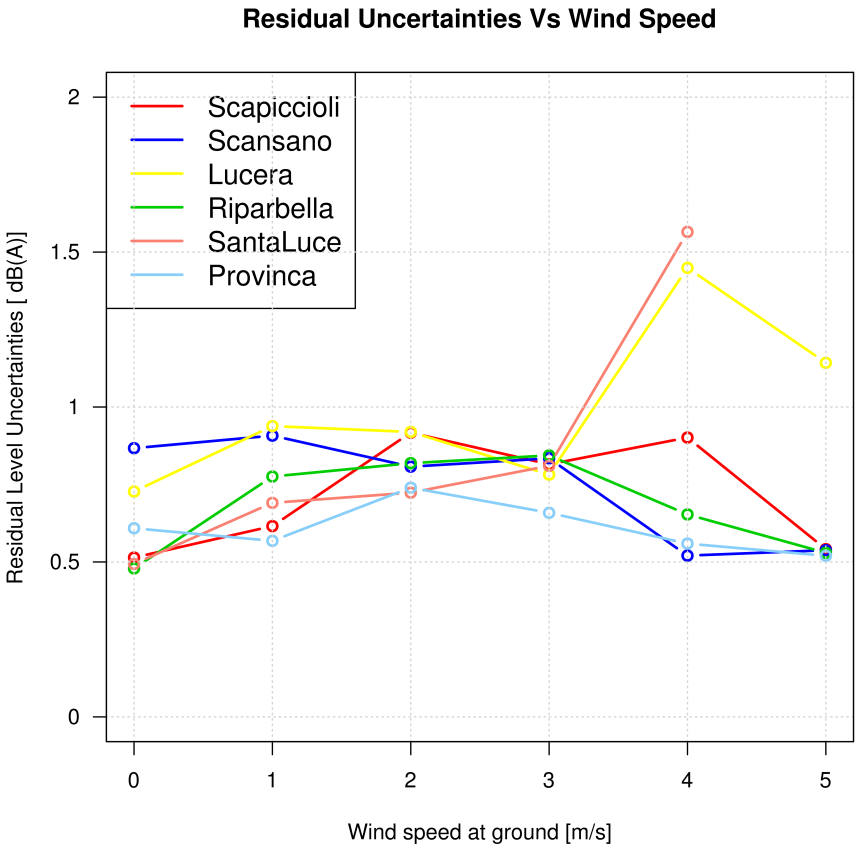

Figure 8: uncertainty on residual noise vs v_{gr} for all the test sites.

4. Conclusions

The new procedure for evaluating the noise emission from operational wind turbines provides a useful approach to technicians and competent bodies in order to monitoring the noise impact on receivers without stopping the farm.

The 95% coverage interval obtained with the Monte Carlo simulations varies from 1.2 to 2.6 dB(A) for noise emission levels and from 1.2 to 1.8 dB(A) for residual levels evaluated over the whole measurement period. This results are suitable for the assessing compliance to normative prescriptions at least in Italy. Higher values has been demonstrated at low wind speeds, where noise data have a bigger spread due to meteorological effects on measurements [12]. This paper presented a very preliminary results. A deeper statistical investigations is in progress [13], also with the aim of evaluating the sensitivity of the procedure to different input parameters and maybe also to reduce the number of parameters itself.

References

[1] G. F. Hessler, D. M. Hessler, P. Brandstätt, K. Bay, "Experimental study to determine wind-induced noise and windscreen attenuation effects on microphone response for environmental wind turbine and other applications", Noise Control Engineering Journal . Jul/Aug2008, Vol. 56 Issue 4, pp. 300-309.

[2] O. Fégeant, "Wind-Induced Vegetation Noise. Part I: A Prediction Model", Acta Acustica united with Acustica, Volume 85, Number 2, March/April 1999, pp. 228-240(13).

[3] O. Fégeant, "Wind-Induced Vegetation Noise. Part II: Field measurements", Acta Acustica united with Acustica, Volume 85, Number 2, March/April 1999, pp. 241-249(13).

[4] K. Bolin, "Prediction Method for Wind-Induced Vegetation Noise", Acta Acustica united with Acustica, Volume 95, Number 4, July/August 2009, pp. 607-619(13).

[5] F. Van der Berg, "Wind profile over complex terrain", Second International Meeting on Wind Turbine Noise, Lyon, 2007.

[6] ISPRA "Linee guida per la valutazione e il monitoraggio dell'impatto acustico degli impianti eolici", Deliberazione del Consiglio Federale seduta del 20 ottobre 2012 – DOC. N. 28/12, 103/2013, http://www.isprambiente.gov.it/files/pubblicazioni/manuali-lineeguida/MLG_103_13.pdf

[7] ISO 9613-2:1996 Acoustics "Attenuation of sound during propagation outdoors - Part 2: General method of calculation".

[8] JCGM 101:2008 Evaluation of measurement data- Supplement 1 to the "Guide to the expression of uncertainty in measurement"- Propagation of distributions using Monte Carlo method.

[9] ISO ENV 13005:1999, "Guide to the expression of uncertainty in measurement".

[10] UNI ISO 1996-2/2007 "Acoustics - Description, measurement and assessment of environmental noise - Part 2: Determination of environmental noise levels"

[11] UNI/TR 11326:2009 Acustica - Valutazione dell'incertezza nelle misurazioni e nei calcoli di acustica - Parte 1: Concetti generali.

[12] L. Fredianelli, G. Licitra et al., "The suitable parameters to assess noise impact of a wind farm in a complex terrain: a case-study in Tuscan hills", Proceedings of Euronoise Prague, 2012.

[13] G. Licitra, L. Fredianelli, et al., "Sensitivity analysis of modelling parameters in wind turbine noise assessment procedure", Outgoing in Proceedings of the 22th ICSV Florence, 12-16 july 2015.
[14] R Development Core Team (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.