Poster3-62

A STATISTICAL METHOD FOR ESTIMATION OF WIND FARM INFLUENCE ON RADAR DATA AND ITS MITIGATION

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1. INTRODUCTION

For the Canadian weather radar network, Environment and Climate Change Canada (ECCC) wishes to assess impact of wind turbines on our data. If it is possible to collect radar data for certain period before and after wind farm installation, than the proposed statistical methodology can be used as an objective tool for estimation of level of contamination of radar data due to wind farm. Also, the methodology is applicable to estimate efficiency of a mitigation technique.

Depending on distance and topography, the rotating blades and tower of wind turbines can impact weather radar data. To minimize or eliminate negative effects of wind farms on weather radar data, various methods have been suggested (Norin, 2015, 2017; Moruzzis & Perret, 2014; Nai & Torres, 2011). To accept a mitigation solution it is essential to have a reliable objective methodology for determining a level of radar data contamination and its reduction.

The accurate estimation of the potential impact of the wind farm on weather radar data is a complex task and existing methods are not satisfactory. This study is trying to come closer to that accomplishment.

The suggested methodology is described as a physical concept and mathematical procedure as well. Four elements underlie the methodology. First is formulation of variables that have normal distributions, which are relative disturbances of radar reflectivity (Z) and radial velocity (V). Second is use of the Mann Whitney U test as statistical tool for comparison of the distribution shapes and acceptance/rejection of hypotheses that two distributions are likely derived from the same population. The third element is processing radar data not just bins immediately above wind turbines, but rather a grid of neighboring bins (9 or 12). Therefore it was possible not just to establish a reference Z or V value for quantification of deviation, but also to evaluate a spatial domain of wind turbine influence. The last element is decomposition of processed data as attempt to reduce number of variables that influence homogeneity of populations. The goal was to analyze impact of wind turbines as a dominant factor of possible influence on contamination of Z or V radar data.

To demonstrate the methodology it was applied on real data. For different wind farms and radars the conclusions will vary. Mitigation efficiency was also shown. The purpose here is to show how to use the method, not the results of it.

2. METHODOLOGY

The proposed statistical methodology (SM) is analyzing two radar moments: the radar reflectivity factor (reflectivity Z) and radial velocity (V). The methodology hereafter referred to as ZV SM.

2.1 *Physical description of ZV SM*

If we select an undisturbed point (radar bin) at which we have been collecting data for a certain time period during the operational Doppler radar scanning we can create a distribution of the collected values (like in Figure 1). However, it is unsuitable to use it for monitoring influences of some other factors such is wind turbine.

Most of the time the undisturbed bin value will be close to a local average value of surrounding radar bins and most likely above or below it with equal frequency. If this disturbance (deviation, offset) is divided by a local average value we will get transformed variable called *relative disturbance*, which should approximately have the shape of a normal distribution. That is consequence of more or less homogenous spread of the Z or V values or when that is not a case during the time the inhomogeneity was spread equally during a longer period (for example the storm cells during summer). This distribution we will call a “reference distribution” of relative disturbance.

If a wind turbine (WT) was installed in the vicinity of the selected point (radar bin) and we subsequently repeat the previously described procedure we will get relative disturbance in presence of the WT. We will call this distribution the “WT distribution”. If impact of the WT is significant than the distribution shape of relative disturbances will be significantly different from the reference distribution.

We can use a statistical test to evaluate the difference between the reference and WT distributions of relative disturbance. If the test shows that two distributions are likely derived from the same population than there was not a significant influence of WT on the analyzed radar data. However, if WT impact was significant than the statistical test would show that those two distributions are not from a same population.

To estimate efficiency of applied mitigation we will repeat the described procedure using a “mitigation distribution” that is created using data that has had the mitigation method applied to the data that contained WT echoes.

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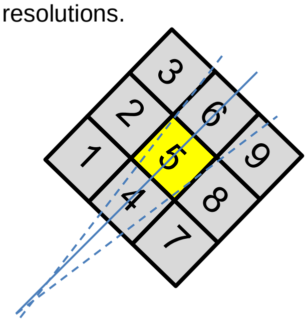
2.2. *Mathematical description of ZV SM*

The ZV SM application for a wind farm (WF) with N wind turbines has following steps:

1) From a list of N wind turbine locations (latitude, longitude) determine a closest azimuth and horizontal distances from a radar as horizontal bin coordinates: (α_n, d_n), n=1,N.
2) Chose 2 (or more) control points where WT influence are not expected and determine a closest azimuth and horizontal distances from a radar as the bin coordinates: (α_m, d_m), m=1,2.
3) Since the biggest WT influence are expected at the lowest elevations (β_1) of Doppler radar, convert (α, *d*) radar bin horizontal coordinates to cylindrical coordinates (α, *r*), where $r = \frac{d}{cos\beta_1}$ was rounded to the closest bin range.
4) Map additional sets of 8 surrounding radar bins (grid bin) coordinates (α_{ni}, r_{ni}), n=1,N+2; i=1:9:
$\alpha_{n1} = \alpha_{n5} - \Delta\alpha,$ $\quad r_{n1} = r_{n5} - \Delta r;$
$\alpha_{n2} = \alpha_{n5} - \Delta\alpha,$ $\quad r_{n2} = r_{n5};$
$\alpha_{n3} = \alpha_{n5} - \Delta\alpha,$ $\quad r_{n3} = r_{n5} + \Delta r;$
$\alpha_{n4} = \alpha_{n5},$ $\quad r_{n4} = r_{n5} - \Delta r;$
$\alpha_{n5} = \alpha_n,$ $\quad r_{n5} = r_n;$
$\alpha_{n6} = \alpha_{n5},$ $\quad r_{n6} = r_{n5} + \Delta r;$
$\alpha_{n7} = \alpha_{n5} + \Delta\alpha,$ $\quad r_{n7} = r_{n5} - \Delta r;$
$\alpha_{n8} = \alpha_{n5} + \Delta\alpha,$ $\quad r_{n8} = r_{n5};$
$\alpha_{n9} = \alpha_{n5} + \Delta\alpha,$ $\quad r_{n9} = r_{n5} + \Delta r;$

where $\Delta\alpha$ and Δr are azimuth and range radar resolutions.



5) For a certain period (T_R) before WF installation collect (K_R) the reference radar data Z and V $(Z_{ni}(t_k), V_{ni}(t_k);\ t_k \in T_R$, k=1: K_R) for mapped radar bins (α_{ni}, r_{ni}). For concise writing, we will use $x_{ni}(t_k)$ denotation instead of $Z_{ni}(t_k)$ and $V_{ni}(t_k)$ variables.
6) Transform $x_{ni}(t_k)$ variables to relative disturbance variables $X_{ni}(t_k)$:

$$X_{ni}(t_k) = \begin{cases} \dfrac{x_{ni}(t_k) - \overline{x_n}(t_k)}{\overline{x_n}(t_k)}, & \overline{x_n}(t_k) \neq 0 \\ 0, & \overline{x_n}(t_k) = 0 \wedge x_{ni}(t_k) = 0 \\ 1, & \overline{x_n}(t_k) = 0 \wedge x_{nj}(t_k) \neq 0 \end{cases}$$

$$\overline{x_n}(t_k) = \frac{1}{9}\sum_{i=1}^{9} x_{ni}(t_k)$$

7) For each wind turbine WT_n and grid bin *i* from time series values $X_{ni}(t_k)$ only for $X_{ni}(t_k) \neq 0$ create frequency distribution $F_{ni}(j)$:

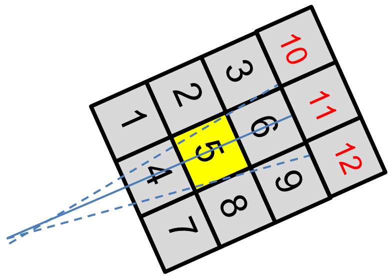
$$F_{ni}(j) = \sum_{t_k} X_{ni}(t_k) \begin{cases} j = 1 & -1 \geq X_{ni}(t_k) \\ j = 2:(j_{mx} - 1); & (j - 1 - \frac{j_{mx}}{2}) * \Delta X < X_{ni}(t_k) \leq (j - \frac{j_{mx}}{2}) * \Delta X \\ j_{mx}; & 1 < X_{ni}(t_k) \end{cases}$$

where total number of bins $j_{mx} = {}^{2}/_{\Delta X} + 2$ and ΔX is bin width of frequency distribution, in our case $\Delta X = 0.05$. First and last bin in the distribution is for values less than -1 or greater than 1. Exclusion of cases when $X_{ni}(t_k) = 0$ was justified from two aspects. First, we are not interested for clear weather conditions and secondly if we include those cases than domination of zero value frequency would dramatically restrict sensibility of U test.
8) For further inter-comparisons and statistical tests we need to convert reference absolute frequency distributions to relative frequency distributions R_{nj}:

$$R_{ni}(j) = \frac{F_{ni}(j)}{G_{ni}},$$

where $G_{ni} \equiv \sum_{j=1}^{jmx} F_{ni}(j)$ is total number of radar measurements on location of nth WT at ith local grid bin during a time period T_R, without cases when $X_{ni}(t_k) = 0$.
9) Identical procedures (5-8) as for the reference relative distributions R_{nj} were applied to get W_{nj} and M_{nj} wind turbine and mitigation relative distributions, respectively. Both distributions were collected during a period T_W after WT were installed.
10) Using the Mann Whitney U test, sometimes called the Mann Whitney Wilcoxon Test (Russell, 2012) we can now test whether two samples are likely derived from the same population (i.e., that the two populations have the same shape). As result of the U test we are getting probability value P_{ni}^{RW} or P_{ni}^{RM} if we were comparing a reference with wind farm distribution or reference with mitigation distribution, respectively.
11) Interpretations of the U test probability values can be done from different aspects. We will point out only three:
    A. *Effect of an individual WT at its location.*
    If P_{ni}^{RW} was less than 0.05 than definitely WT had an influence on analyzed variable x. Also, if at same time P_{ni}^{RM} has greater values than 0.05 (closer to 1) the mitigation was effective.
    B. *Effects of WT in its vicinity.*
    If previous analysis was applied on all *i* (9) grid bins we can get information of WT influence, or mitigation efficiency, not only at radar bin closest to the WT but in the 8 surrounding radar bins. Instead of 9 grid bin we can extend symmetrical or unsymmetrical number and position of grid bins. Because we were expected

more influence behind a WT we were analyzed grid bin with additional row of 3 bins behind the WT, as shown below:



C. *Overall effect from all WT in the wind farm.* For a chosen bin (for WT location, i=5), we will obtain set of P_{n5}^{RW} values (n=1:N). Plotting distribution of those values (converted to percentage: $PP_{n5}^{RW} = P_{n5}^{RW} / \sum_{n=1}^{N} P_{n5}^{RW}$) gives a visual overview of the percentage of WT from the wind farm that contaminated radar data. For a numerical estimation, we need to divide the number of WT with P value less than 0.05 (N_c) with the total number of WT (N).

12) In the case where we want to analyze mitigation efficiency, we apply U test on W_{nj} and M_{nj} distributions. As a result, we will have pairs of probability values P_{ni}^{RW} and P_{ni}^{RM}.
Using scattering diagrams with P_{ni}^{RW} and P_{ni}^{RM} values for the i[th] bin, we can get an overall indication of mitigation efficiency. In general three sceneries are available:
    i. Slope of scatter diagram is 1 ($P_{ni}^{RM} \approx P_{ni}^{RW}$) , then the mitigation didn't significantly change the original data. Less dispersion around 1:1 line gives stronger argument for that. While more dispersion of points indicate that the mitigation was unreliable, sometimes it improved quality of the data but also can make them worse. No consistency of the mitigation.
    ii. Slope is below 1:1 line ($P_{ni}^{RM} < P_{ni}^{RW}$) the mitigation made the WF data even worse.
    iii. Slope is above 1:1 scatter line ($P_{ni}^{RM} > P_{ni}^{RW}$), overall mitigation was successful.

13) Proposed statistical analysis assumes that only one factor (wind turbine) could influence the homogeneity of the data. However seasonal influences or intensity of weather are additional factors that could impact homogeneity of the data. Because of this the previous steps (5-11) of the procedure should be applied on subpopulation of original set of data.

A. Winter and summer data as 2 distinguishable seasons with generally different weather types (stratus versus convective, lower versus higher clouds, dynamically weaker versus stronger clouds, etc.).
B. Relatively to intensity of radar reflectivity, tentatively we can create 4 distinct groups of weather conditions for each winter or summer season (see Figure 1):
    i. Weak: Z < 10 dBZ,
    ii. Medium: 10 dBZ ≤ Z < 20 dBZ
    iii. Strong: 20 dBZ ≤ Z < 30 dBZ
    iv. Severe: 30 dBZ ≤ Z .

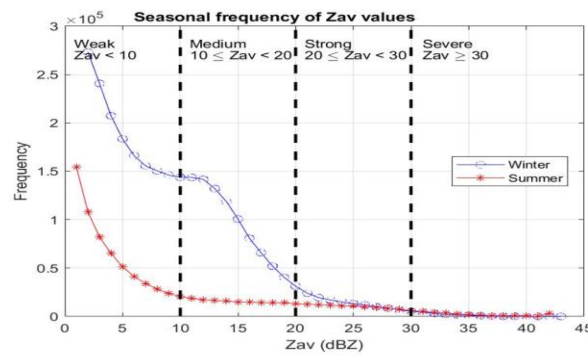


Figure 1. Typical seasonal distribution of radar reflectivity for lowest elevation of Doppler radar for area surrounding the radar location.

3. ILLUSTRATION OF THE ZV METHODOLOGY

To illustrate ZV SM we will present graphs and results obtained from a real data from one of our Doppler radars which covers a wind farm we wish to investigate. To demonstrate the methodology we will apply it on radar reflectivity Z and radial velocity V.

3.1. *Relative disturbance distributions*

First we confirm expected normal distribution of reference relative disturbances for WT #25 at grid bin #5 ($R_{25,5}$) of Z (Figure 2a) for period T_R before WF installation (two summers) and after WF installation (Figure 2b) for a same location and period T_W (one summer).

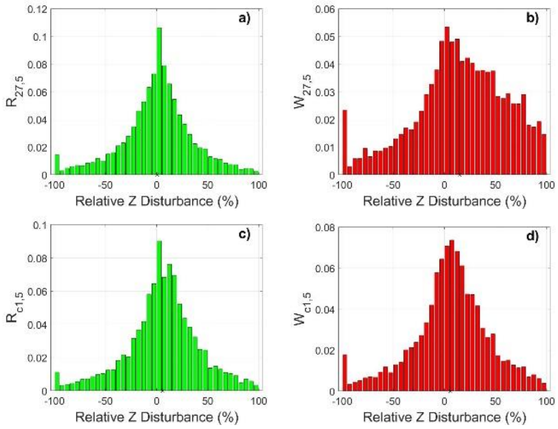


Figure 2: Relative disturbances of Z for WT #25 (top, a & b) and control point #1 (bottom, c & d) at grid bin #5 from a referenced period T_R (left green, $R_{25,5}$ & $R_{c2,5}$) and from WF period T_W (right read, $W_{25,5}$ & $W_{c2,5}$).

To have confidence that the deformed normal distribution of $W_{25,5}$ was not influenced by non WT impacts, the same graphs but for test point #1 are presented on Figure 2c,d. As we can see, both distributions before and after WF are the same, normal, which confirmed our crucial assumption that without WT distributions would be the same from season to season.

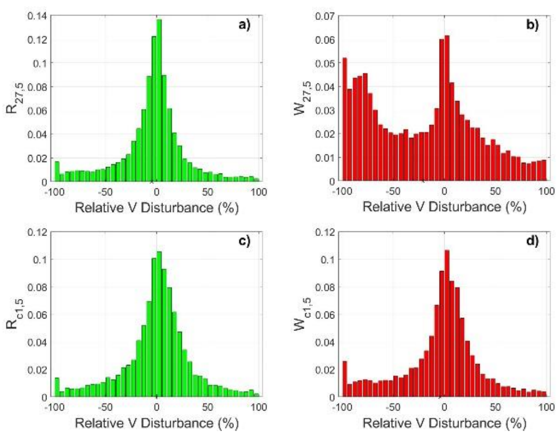


Figure 3: Relative disturbances of V for WT #25 (top, a & b) and control point #1 (bottom, c & d) at grid bin #5 from a referenced period T_R (left green, $R_{25,5}$ & $R_{c2,5}$) and from WF period T_W (right read, $W_{25,5}$ & $W_{c2,5}$).

Similar graphs are presented on Figure 3a,b,c,d for relative disturbances of radial velocity V.

3.2. *Effects at location of WT*

We will apply U test on the same #25 WT to see if the WT significantly contaminated Z or V radar data. Results of the U test comparisons of $R_{25,5}$ and $W_{25,5}$ distributions gave us 0.17 and 0.01 p-values for Z and V variables, respectively. We took the conventionally accepted threshold of 0.05 for rejection of a null hypotheses that two distributions are likely derived from the same population. Therefore we can say that the WT #25 contaminates radial velocity (0.01 < 0.05), while for radar reflectivity we can see some negative impact of WT (0.17 > 0.05) but still we cannot reject hypotheses that it was variation of Z value regardless of the WT installation.

3.3. *Effects in vicinity of WT*

Applying the U test to the rest of 12 pairs of distributions ($R_{25,j}$ and $W_{25,j}$; j=1:12) for grid bins in a vicinity of the WT #25 (yellow box on Figure 4) we are getting spatial variation of WT effects on radar data contamination in vicinity of WT.
From Figure 4 we can see that reflectivity Z (left) was above the 0.05 threshold in all grid bins. Boxes with orange color indicate grid bins with P values smaller than value at WT location (0.17). For radial velocity V (right) in all 9 grid bins the P value was below the 0.05 threshold, which indicates that WT impact is not only at WT location but also in surrounding bins, excluding the additional row behind the WT (green).

Z

0.19	0.26	0.18
0.15	0.09	0.13
0.22	0.17	0.15
0.23	0.22	0.25

V

0.19	0.10	0.10
0.02	0.01	0.03
0.01	0.01	0.02
0.03	0.02	0.05

Figure 4: Spatial variation of P values obtained from U test for 12 grid bins of WT #25 for summer radar data for Z (left) and V (right). Yellow box is location of WT.

3.4. *Overall impact of WT*

To estimate the overall impact of wind turbines in a wind farm, we can use graphs of distributions (relative number of WT in WF) of P values, Figure 5 and 6 for Z and V variables, respectively.

In all graphs the resolution of P values is 0.05. Therefore, the first bar on Figure 5a and Figure 6a represent the relative number of WT that with certainty of more than 95% have significant impact on Z or V radar data. In our example for summer data for radial velocity V, about 80% of WT belong to that category (Figure 6a) while for reflectivity Z it is less than 10% (Figure 5a). At the same time, comparisons for data exclusive before installation of WF, Figures 5b, or after installation (Figure 5c), give P values on all WT that are, as expected, much greater than critical 0.05 value.

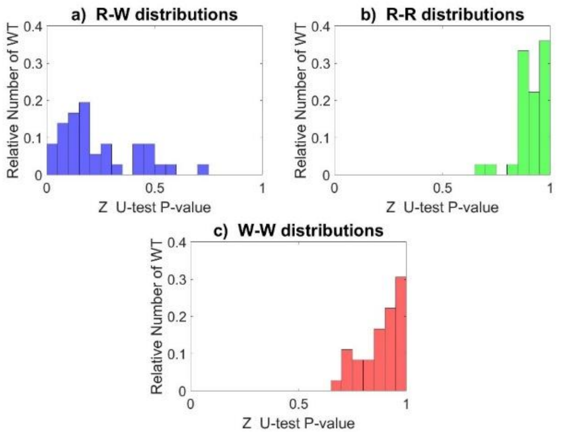


Figure 5: Distributions (relative number of WT in WF) of P values for Z disturbance comparisons between $R_{n,5}$ and $W_{n,5}$ (a), $R_{n,5}$ and $R_{n,5}$ (b), $W_{n,5}$ and $W_{n,5}$ (c).

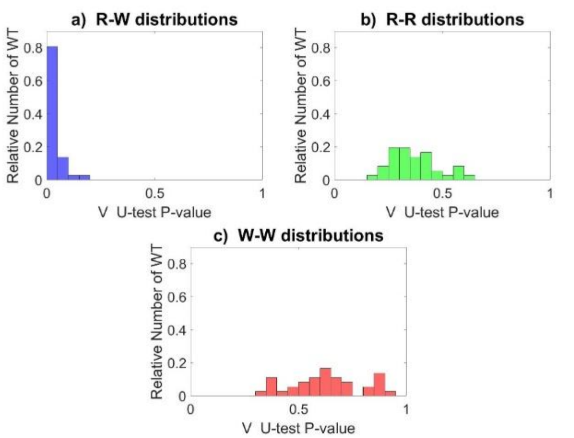


Figure 6: Distributions (relative number of WT in WF) of P values for V disturbance comparisons between $R_{n,5}$ and $W_{n,5}$ (a), $R_{n,5}$ and $R_{n,5}$ (b), $W_{n,5}$ and $W_{n,5}$ (c).

3.5. *Mitigation efficiency*

As an example of mitigation efficiency analysis, we will explore scatter diagrams of pairs of probability values P_{n5}^{RW} and P_{n5}^{RM}.

From Figure 7 we can see that the mitigation didn't improve contamination of summer radar data since P values are almost the same (slope is 1).

With decomposition of the data regarding the intensity of radar reflectivity (as described in 2.2. 13b) the mitigation showed some influence. For reflectivity Z it was unreliable (Figure 8), even negative for severe weather (slope 0.87, Figure 8d). For radial velocity V, (Figure 9) the slope was always greater than 1 and the most improvement mitigation had for severe weather conditions (Figure 9d). The efficiency of mitigation would be the most beneficial if improvement was for smaller P values, but that was not the case and therefore the applied mitigation software was not so successful.

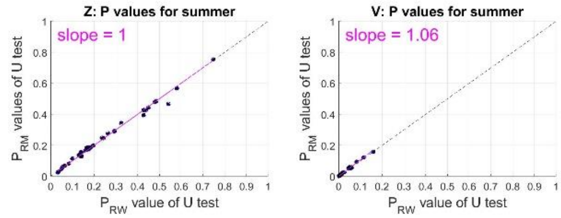


Figure 7: Scatter diagrams of P values of U test for "reference distribution"- "WT distribution" (P_{RW}) and "reference distribution"- "mitigation distribution" (P_{RM}) for summer data for radar reflectivity Z (left) and radial velocity V (right).

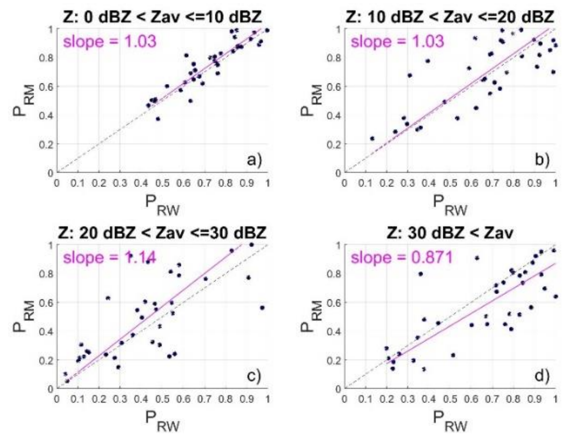


Figure 8: Scatter diagrams of P values of U test for "reference distribution"- "WT distribution" (P_{RW}) and "reference distribution"- "mitigation distribution" (P_{RM}) for summer data for radar reflectivity Z for 4 group of weather conditions: weak (a), medium (b), strong (c), and severe (d).

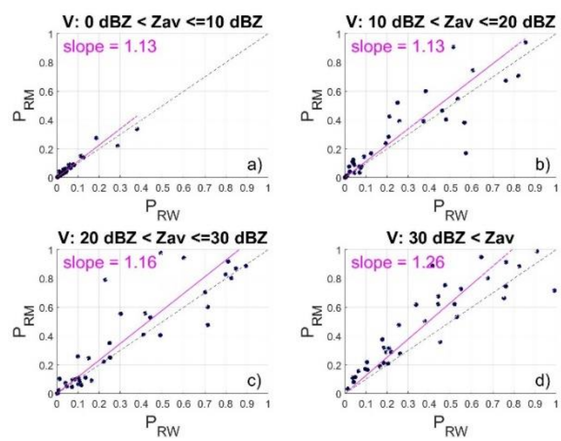


Figure 9: Same as for Figure 8 but for radial velocity, V.

4 SUMMARY

The suggested methodology is described as a physical concept and mathematical procedure as well. Four elements underlie the methodology.

1) Formulation of variables that have normal distributions, which are relative disturbances of radar reflectivity (Z) and radial velocity (V);

2) Use of the Mann Whitney U test as statistical tool for comparison of the distribution shapes and acceptance/rejection of hypotheses that two distributions are likely derived from the same population;
3) Processing radar data not just bins immediately above wind turbines, but rather a grid of neighboring bins. Therefore it was possible not just to establish a reference Z or V value for quantification of deviation, but also to evaluate a spatial domain of wind turbine influence;
4) Decomposition of processed data as attempt to reduce number of variables that influence homogeneity of populations. The goal was to analyze impact of wind turbines as a dominant factor of possible influence on contamination of Z or V radar data.

The methodology was applied on real data with three outcomes:

1) Effect of an individual WT at its location;
2) Effects of WT in its vicinity;
3) Overall effect from all WT in the wind farm.

For different wind farms and radars the conclusions will vary. Mitigation efficiency was also shown. The purpose was to show how to use the method not the results of it.

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