INTERNATIONAL ACOUSTICS RESEARCH ORGANIZATION

Report on Harmonic Prominence and Correlation Analyses at Dochroyle, Scotland

February 2021

International Acoustics Research Organization

IARO Is an international group of researchers with a mission to investigate acoustical environments, especially with respect to features that affect humans and animals, and to publish the results. IARO holds the ethics approval for the CSI-ACHE, the Citizen Science Initiative into Acoustical Characterisation of Human Environments, the results of which are publicly disseminated.

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A. BACKGROUND

Dochroyle is one of a number of residences near Barrhill, Scotland situated near several of Industrial Wind Turbine (IWT) power stations, the closest of which are Arecleoch, Kilgalioch and Mark Hill. The residents wish to study the noise characteristics from the IWTs in these wind power stations to investigate and test the correlation of these noise characteristics to health impacts.

Disclaimer

a. The authors of this review are not party to anti-technology sentiments.

b. Wind turbines are considered by the authors as welcome additions to modern technological societies.

c. The review provided herein has one, and only one, agenda - that of pure scientific inquiry.

d. In no way can or should this scientific review be construed as a document arguing for or against the implementation of wind turbines, or any other industrial complexes.

e. There are no commercial, financial or professional agreements (contractual or otherwise) between the authors of this Review and any persons or parties involved in the wind turbine sector or persons or parties who stand against the implementation of wind turbines.

f. This Report was provided *pro bono*.

Goal

To investigate the infrasound and low frequency noise at the Dochroyle residence, with particular regard to noise immission from neighbouring wind power stations, and test their correlation with health symptoms.

Ethics Approval

This research was performed as part of the Citizen Science Initiative for Acoustic Characterization of Human Environments (CSI-ACHE), the research protocols for which have been approved by the New Zealand Ethics Committee (application number NZEC19_12).

B. DATA GATHERING

1. Recordings were taken at the Dochroyle residence between November 30th and December 6th, 2020, and between February 28th and March 6th, by the residents using an SRA System from Smart Technologies, Palmerston North, New Zealand.

Figure 1: Dochroyle residence showing the two bedrooms with bay windows on the upper floor.

2. The microphones were placed in the East Bedroom (Blue channel) and West Bedroom (Red channel) on stands as shown in Figure 2.

Figure 2: Positioning of the two microphones (Blue – top and Red – bottom).

3. The East bedroom is 5.97 m from bay window to the opposite wall (which the bedhead abuts) and 2.92 m across. The microphone is 0.42 m from the side wall and 0.61 m from the bedhead wall. Note: This is the bedroom the resident slept in.

4. The West bedroom is 4.5 m from the bay window to the fitted cupboards and 3.2 m across. The microphone is placed 1.47 m from the bay window and in the middle of the 1.83 m bay window space.

5. Weather information was downloaded from the MetroBlue site for the Barrhill weather station, with data in one-hour intervals.

6. Sleep diaries were kept by the residents over the course of the recordings (see App 1 and Annex 3).

7. Sleep diaries were also kept by neighbours in the Shallochwell and Knockroon residences (see App 2 & 3) for the 2020 recordings.

C. ANALYSES

1. Every 10-minute file in the recording interval (2:40am, 29th November 2020 to 6:50am, 6th December 2020) was processed.

2. Standard frequency analysis was carried out using narrow-band filters of 1/36th octave adhering to both ANSI® S1.11-2004 and IEC 61260:1995 standards.

3. Sonograms were produced for each 10-minute interval as well as a harmonic analysis to identify harmonic series, and a harmonic prominence analysis (see Annex 1).

4. Prominence is the level of a peak above the background as shown in figure 3.

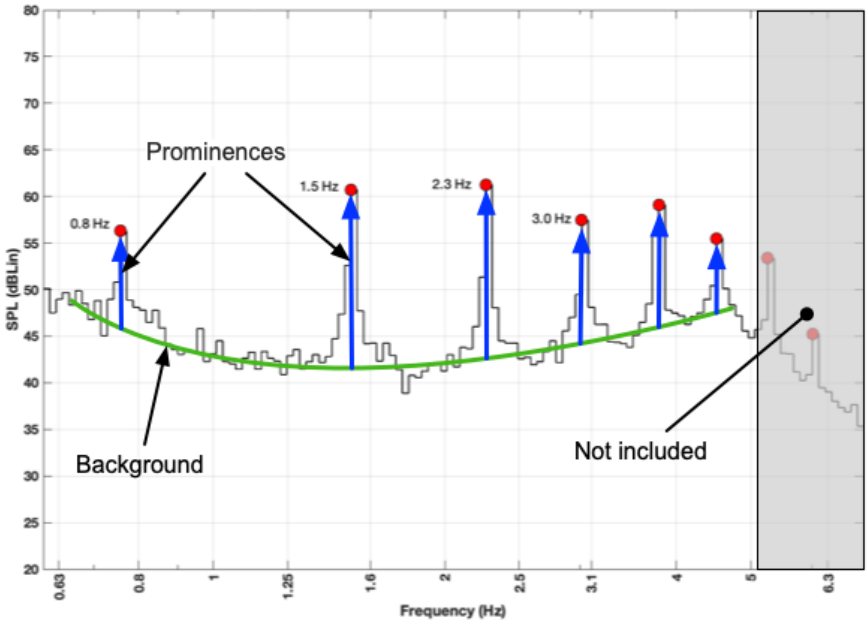


Figure 3: Prominence of a series of harmonic peak (blue) above the background (green).

5. The harmonic and harmonic prominence analyses from the entire recording period were used to identify the most significant harmonic series, and its fundamental frequency. A further harmonic prominence analysis was then run on the entire recording period at this fundamental frequency.

6. The harmonic prominence analyses were combined to produce time-of-day plots indicating the levels of harmonic prominence for the identified fundamental frequency.

7. Harmonic prominence wind roses were created from the harmonic prominence analyses and weather data from the Barrhill weather station (55°05'18.2"N 4°47'02.0"W), which lies 3.7 km almost due north of Dochroyle.

8. The sleep diary for Dochroyle was analysed into a series of wake events at the times noted. Each event was given the Sleep Quality Score noted in the diary for that night.

9. The definition of the Sleep Quality Score was provided by Dr Chris Hanning, a sleep specialist. It used a horizontal, linear, analogue scale, a horizontal line 10cm long (exactly), one end marked "worse sleep ever", other end marked "best sleep ever." The resident made a short vertical mark which corresponded to their assessment of the previous night as soon as they woke in the morning, before drawing curtains.

10. The Sleep Quality Score was measured using a simple ruler and rounded to the nearest integer.

11. Body temperatures noted at various times by the resident of Dochroyle were also taken from the Dochroyle sleep diary.

12. The Sleep Quality Score and temperature were used in a Spearman Rank Correlation analysis (Annex 2) against the mean harmonic prominence values for the hour prior to the event.

13. For the March 2021 recordings, another type of diary was used, which allowed "Noise perception," "External vibration perception," and "Internal body sensation" to be graded on a 5-point scale.

14. These were also used in a Spearman Rank Correlation analysis (Annex 2) against the mean harmonic prominence values for the hour prior to the diary entry.

D. RESULTS AND DISCUSSION

Frequency Analysis

1. Figures 4 and 5 show representative results for each of the two channels. In this case 'representative' means that the features shown were present in the large majority of the recordings, both more and less pronounced. Other features were present in some of the recordings.

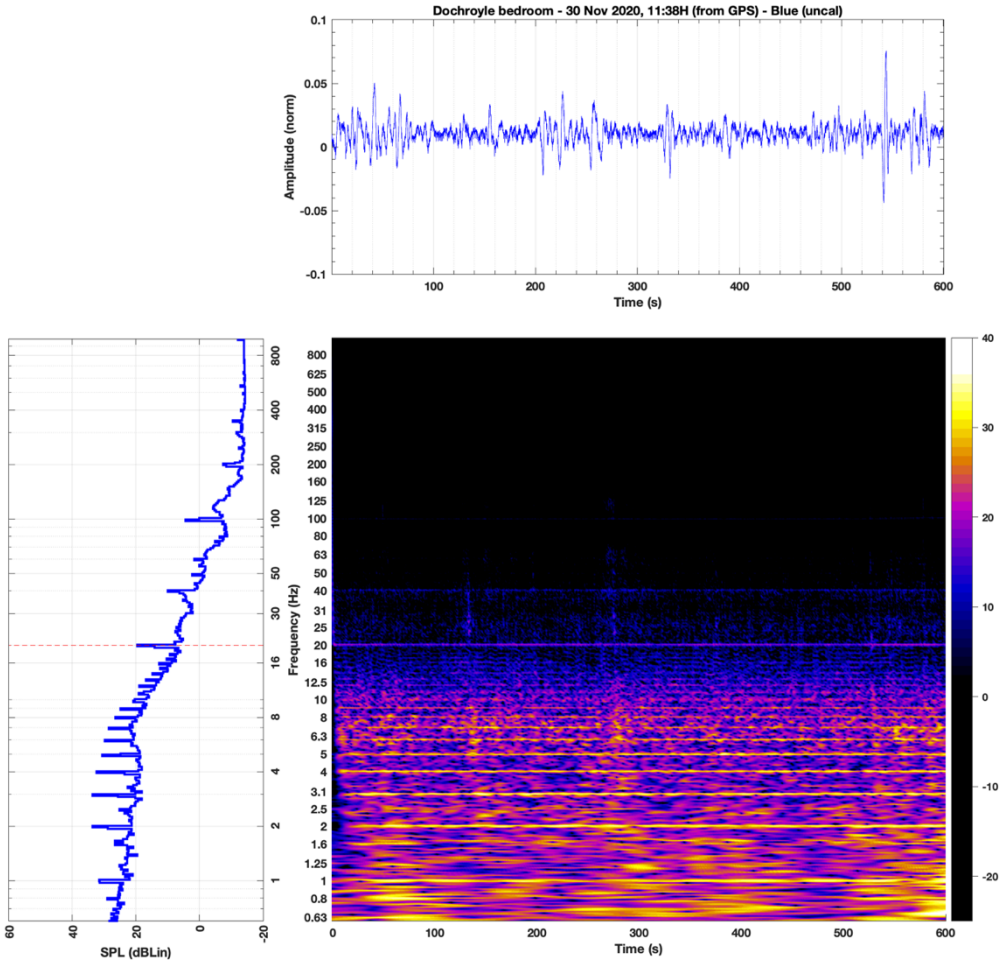


Figure 4: Representative sonogram (bottom right), periodogram (bottom left) and time signal (top) for the Blue channel of the recording.

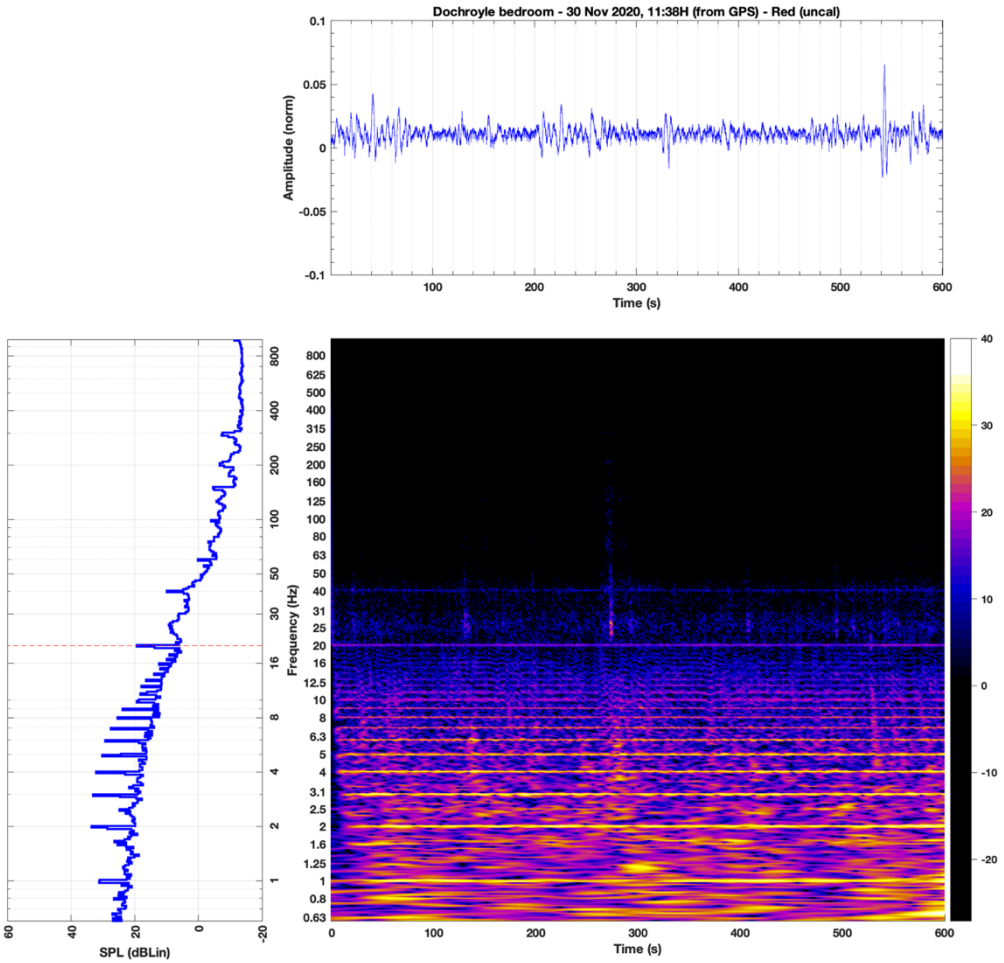


Figure 5: Representative sonogram (bottom right), periodogram (bottom left) and time signal (top) for the Red channel of the recording.

2. Both show a dominant harmonic series in the infrasound region (below 20 Hz) of the spectrum (horizontal lines in the sonograms and peaks in the periodograms of Figures 3 and 4).

3. The level of the background noise in this region of the spectrum does not often exceed 30 dB.

4. The fundamental frequency of the harmonic series is 1 Hz as indicated in the following harmonic analysis (see figure 6).

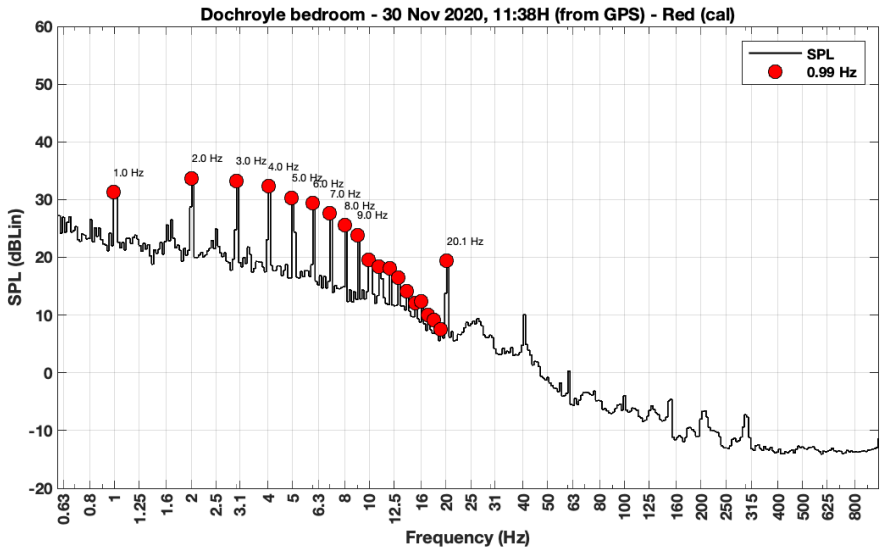


Figure 6: Harmonic analysis of the Red channel (Figure 5).

5. Such a harmonic series is indicative of Wind Turbine Acoustic Signature (WTAS).

6. The IWTs in two of the neighbouring wind power stations, Arecleoch and Mark Hill, are manufactured by Gamesa, models G80-2000 and G87-2000, respectively. These are asynchronous turbines with constant blade-pass frequencies of 1 Hz when running at operational speed.

7. This harmonic series is the WTAS of the turbines in one or both of Arecleoch and Mark Hill.

8. The Kilgalioch wind power station has Gamesa model G114-2500 IWTs, which are also asynchronous but with a blade-pass frequency of 0.75 Hz.

9. This series shares the harmonic frequency of 3 Hz with the 1-hertz series, which completely dominates the 0.75-hertz series. A harmonic prominence analysis at this blade-pass frequency cannot, therefore, be made as the 1-hertz series is present for almost the entire recording period.

10. The tone at 20 Hz (horizontal line at 20 Hz in the sonograms and peak at 20 Hz in the periodograms of Figures 3 and 4) is of unknown origin but varies in level with the WTAS, which indicates that it is associated with it. It appears to be the fundamental frequency of another harmonic series with peaks at 20, 40 and 60 Hz and may represent a resonant frequency of the wind turbines, such as flexing of the blades.

Time-series Analysis

1. Figures 7 and 8 show the recordings from 2:40am on December 1st, 2020 for the Blue and Red channels, respectively.

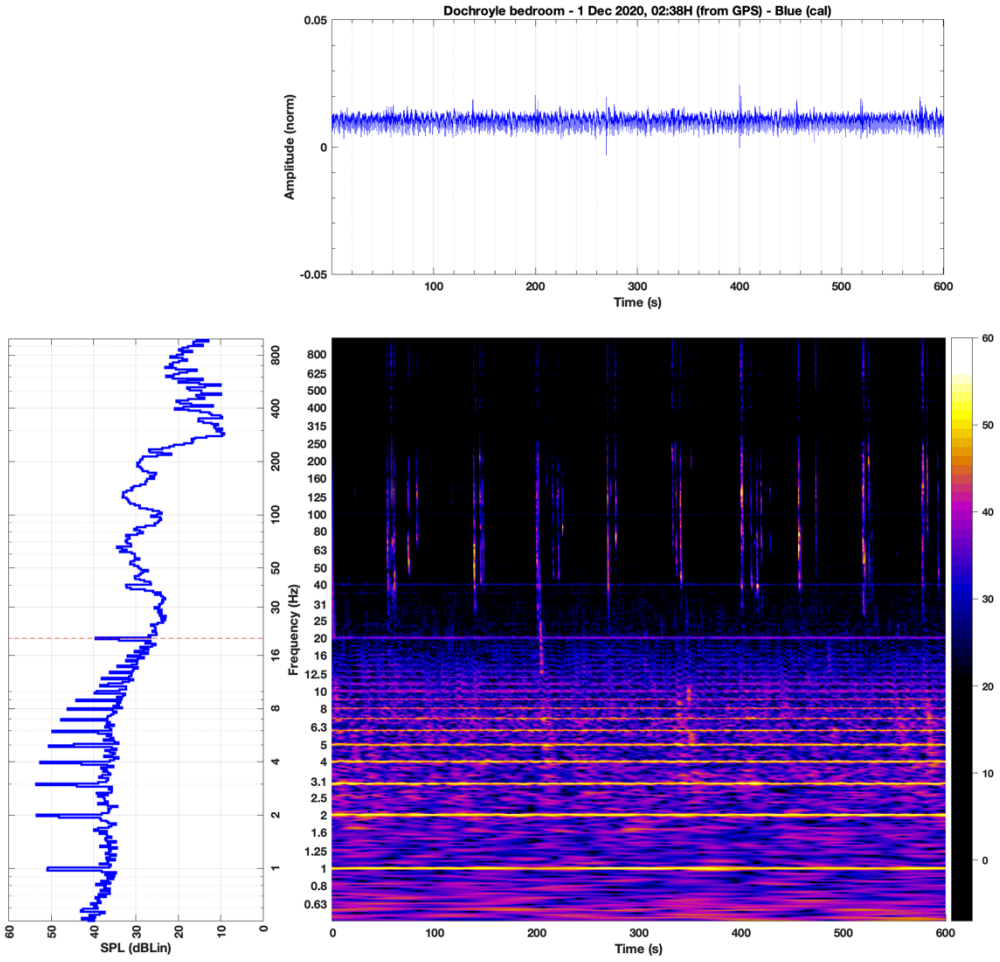


Figure 7: Sonogram (bottom right), periodogram (bottom left) and time-series signal (top) for the Blue channel of the recording.

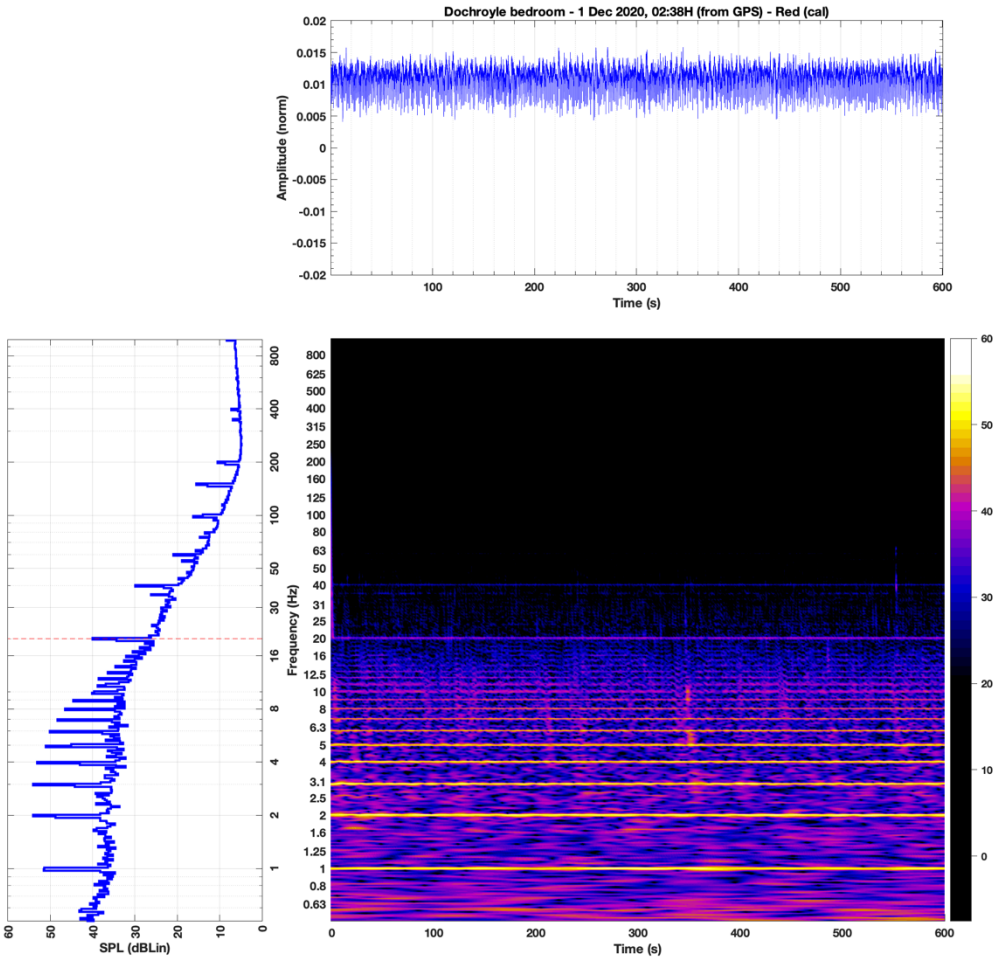


Figure 8: Sonogram (bottom right), periodogram (bottom left) and time-series signal (top) for the Red channel of the recording.

2. The spaced, vertical lines in the Blue-channel results are the snores of the resident. Note that time between snores—roughly 45 seconds—indicates that the resident was suffering from moderate sleep apnoea, which can be a symptom of Wind-Turbine Syndrome.

3. Both recordings show dominant WTAS below 20 Hz and a single, 20-hertz tone of 40 dB. The Red channel shows further tones at 40, 60, 80 and 100 Hz, suggesting that the 20-hertz tone is the fundamental frequency of a harmonic series, as noted in the previous section, item 10. These higher-frequency peaks are masked by snoring in the Blue Channel.

4. Representative time-series signals for 10 seconds of both channels are shown in Figure 9.

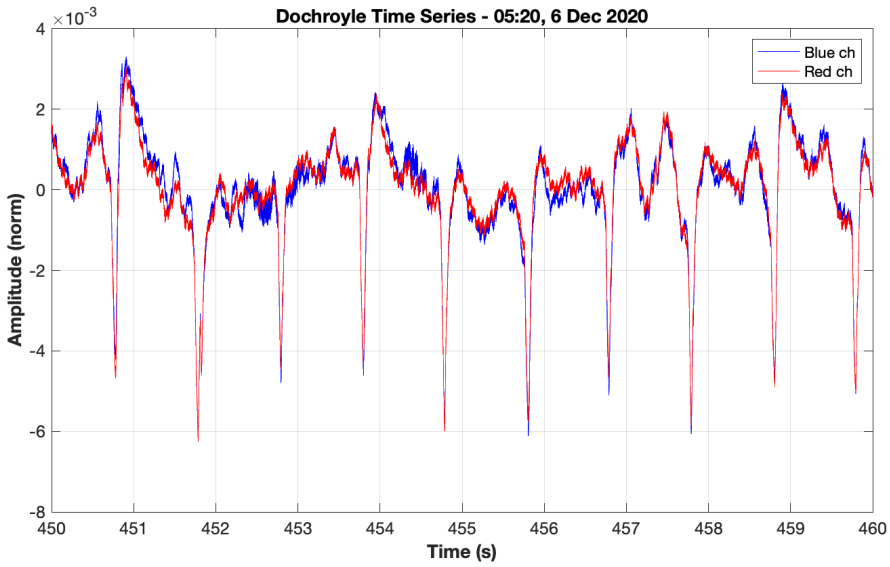


Figure 9: Time series from both Blue and Red channels.

5. The large, negative-going pulses from the IWTs are clearly seen recurring every second, simultaneously in both recording locations.

6. Figure 10 shows the same 10 seconds of recording but converted into sound pressure level (SPL) in deciBels with an averaging time of 5 ms. Also shown in the same figure is the average sound level over the entire 10-minute recording ($SPL_{eq\ 10min}$) and the sound level of the largest harmonic peak of the WTAS.

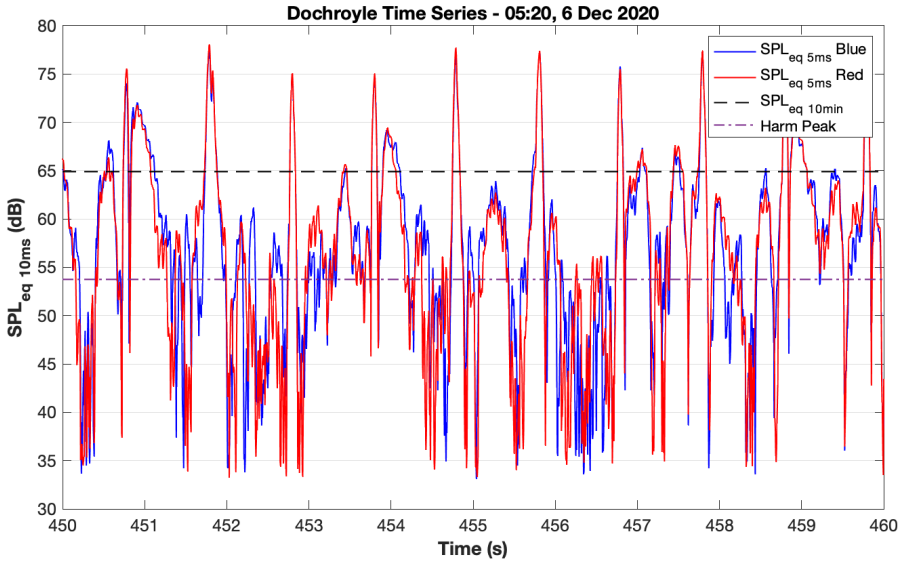


Figure 10: The $SPL_{eq\ 5ms}$ of the same 10 seconds shown in Figure 9.

7. The negative-going pulses of Figure 9 have changed to positive-going pulses (peaks) in Figure 10, since reducing the local pressure requires energy just as increasing the local pressure does.

8. While the traces from the two channels differ, due to the different ambient noises in the two bedrooms, the peaks are seen to be the same for both. This indicates that the source of the pulses is equidistant from the two rooms and almost certainly outside and some distance away.

9. Note that the sound levels here are much higher than in the periodograms of Figures 7 and 8, as the levels here represent the level of the sound over all frequencies i.e., each pulse includes the energy from all of the harmonics. Thus, the periodograms show average sound levels of roughly 40 dB while the overall, zero-weighted sound levels ($SPL_{eq\ 10min}$) are close to 65 dB.

10. The $SPL_{eq\ 5ms}$ is numerically almost identical to the instantaneous peak value converted into deciBels. Since this measure causes fewer issues computationally, and provides more clarity in graphs, it will be used instead of the instantaneous peak value.

11. The WTAS pulses occur at 1-second intervals and have a peak level of 75 dB or more. (Normal conversation is normally considered to be roughly 65 dB.)

12. The peaks are distinct throughout most of the recording(s) suggesting that the immissions come predominantly from one or two IWTs.

13. Averaging the sound levels over 10 minutes does not adequately represent impulsive sound, such as the WTAS seen here. For instance, a gun fired sometime during a 10-minute recording does not materially increase the 10-minute average sound level but is clearly very significant.

Harmonic Prominence Analysis

1. A harmonic prominence analysis was used to identify if there was evidence of significant harmonic series within the recording periods. Figures 11 and 12 show the harmonic prominence for each 10-minute recording, plotted against its fundamental frequency (top) as well as the frequency histogram of the fundamental frequencies, i.e., number of 10-miinute recordings with a given fundamental frequency.

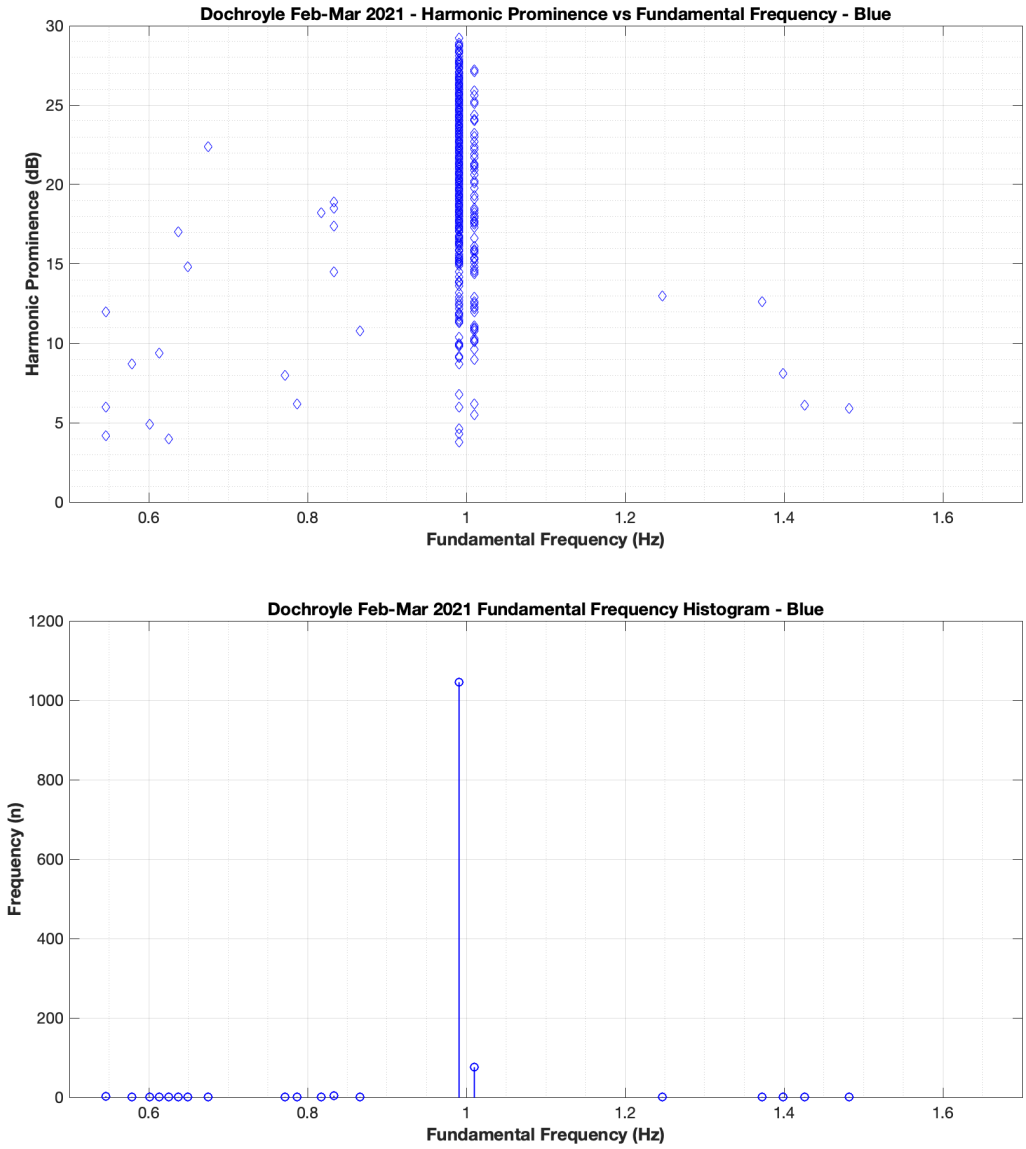


Figure 11: Harmonic prominence for each 10-minute recording period as a function of its fundamental frequency (top) and a frequency histogram of the fundamental frequencies of each 10-minute recording period (bottom).

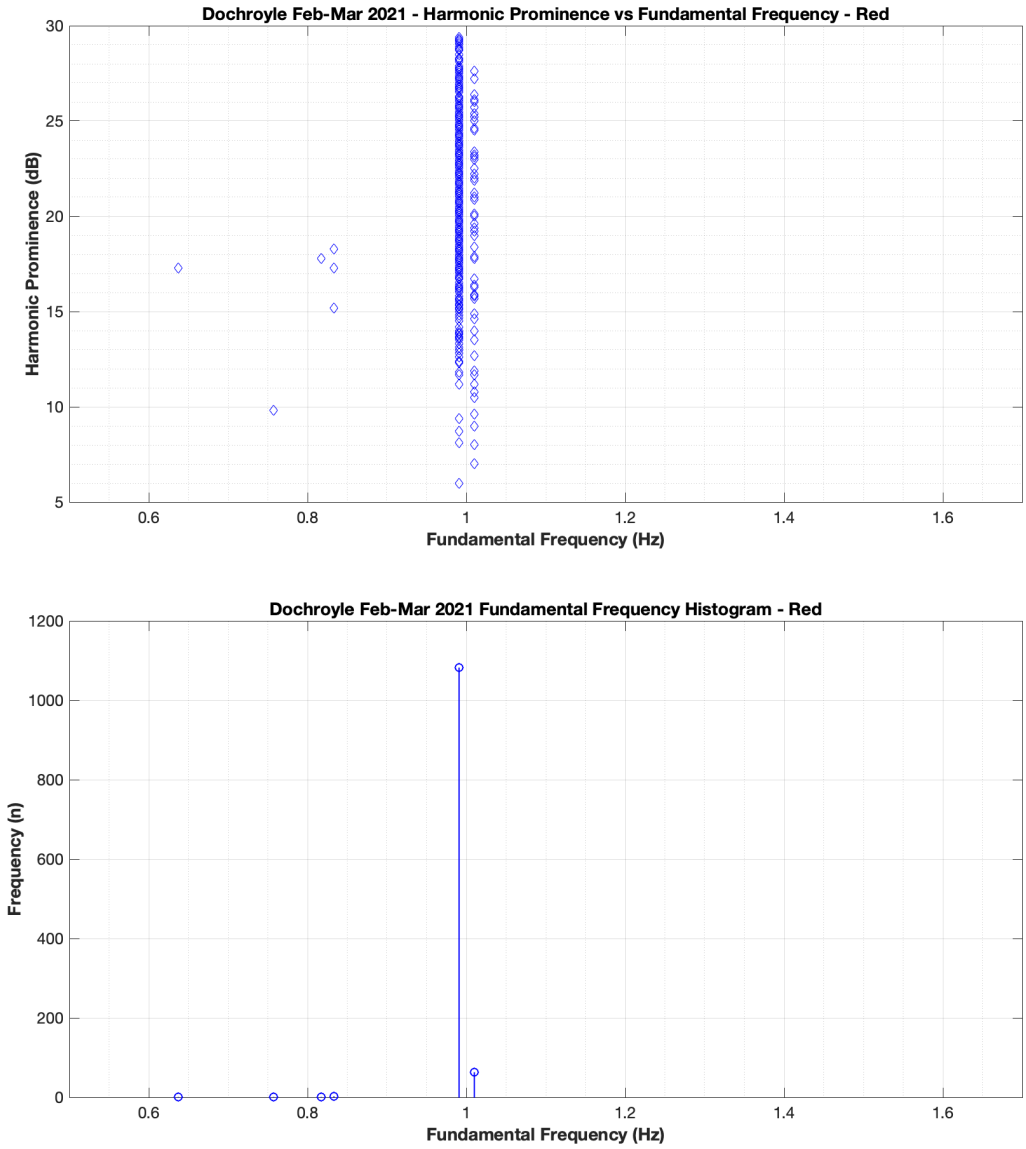


Figure 12: Harmonic prominence for each 10-minute recording period as a function of its fundamental frequency (top) and a frequency histogram of the fundamental frequencies of each 10-minute recording period (bottom).

2. Figures 11 and 12 indicate that almost all of the recordings over this recording interval are dominated by a harmonic series with a 1-hertz fundamental frequency. The twinning peaks, just above and below this frequency, indicate that there is a small amount of variation in the frequency over this time.

3. These results (as well as figures 4 to 10) support carrying out a harmonic prominence analysis with a 1-hertz blade-pass frequency over the two recording intervals. This produced the following Time-of-day plots (see figures 13–16). These show the harmonic prominence for each 10-minute recording as a horizontal bar, with the colour showing the severity of the harmonic prominence in deciBels. The vertical axis is the time of day and the horizontal axis is the day (date).

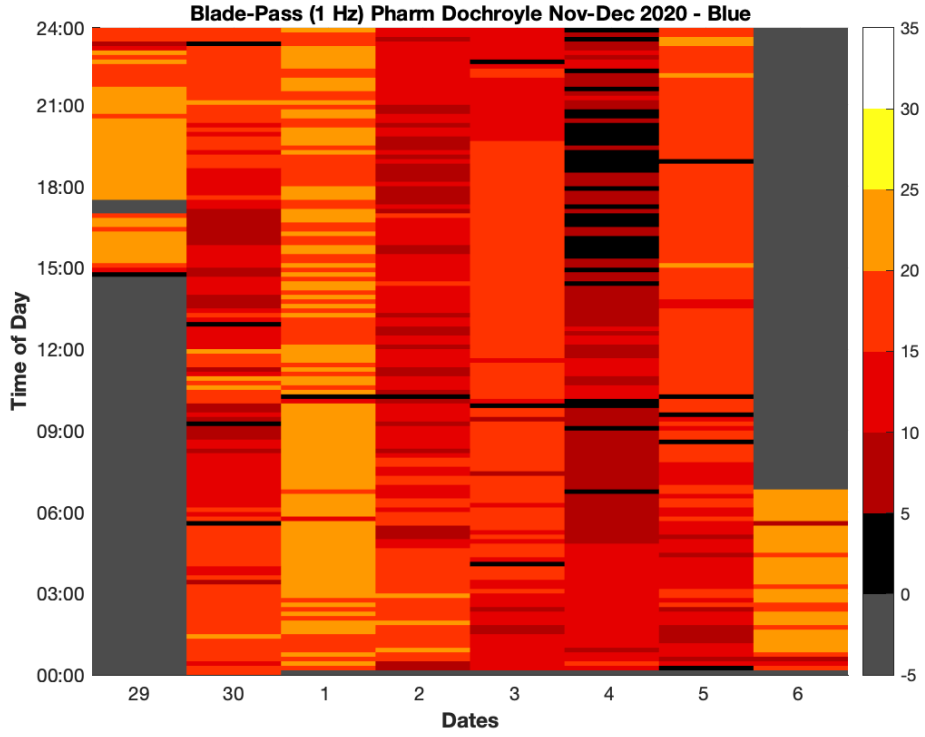


Figure 13: Blade-pass Harmonic Prominence Time-of-day for Blue channel from November 29th to December 6th, 2020. (Grey represents no measurement.)

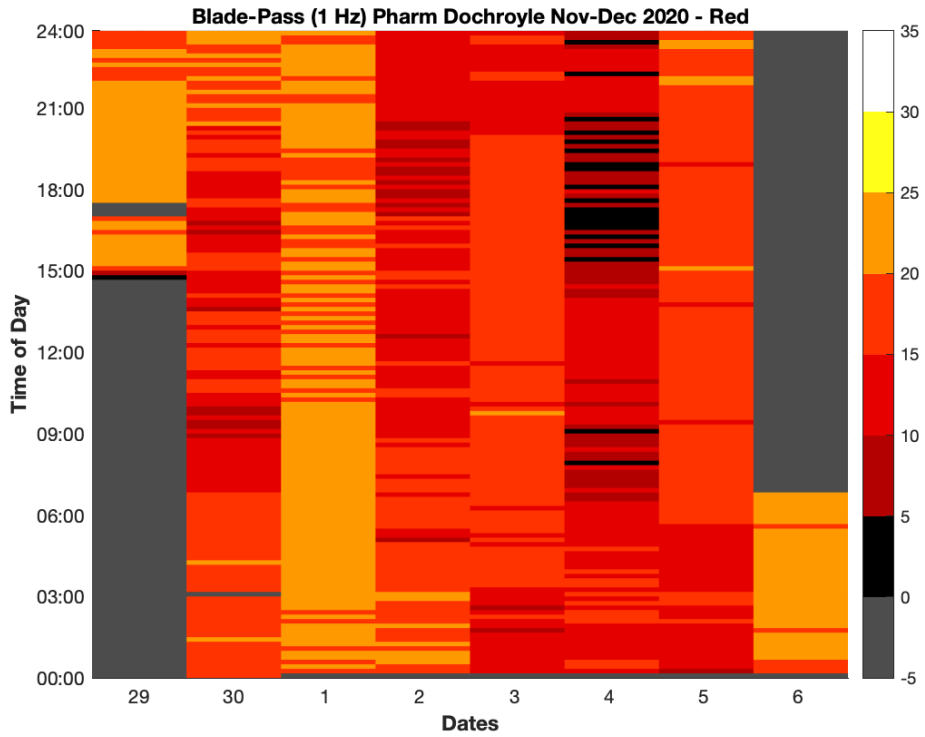


Figure 14: Blade-pass Harmonic Prominence Time-of-day plot for the Red channel from November 29th to December 6th, 2020. (Grey represents no measurement.)

4. Both of these plots show that the harmonic prominence levels ranged between 5 and 25 dB over the entire recording period, apart from the evening of December 4th and a short time in the morning of the same day (black bands), which were less than 5 dB.

5. The authors of this report have never encountered levels as high and as sustained as these plots show.

6. The majority of the evening of November 29th and the majority of December 1st had harmonic prominence levels over 20 dB (orange bars).

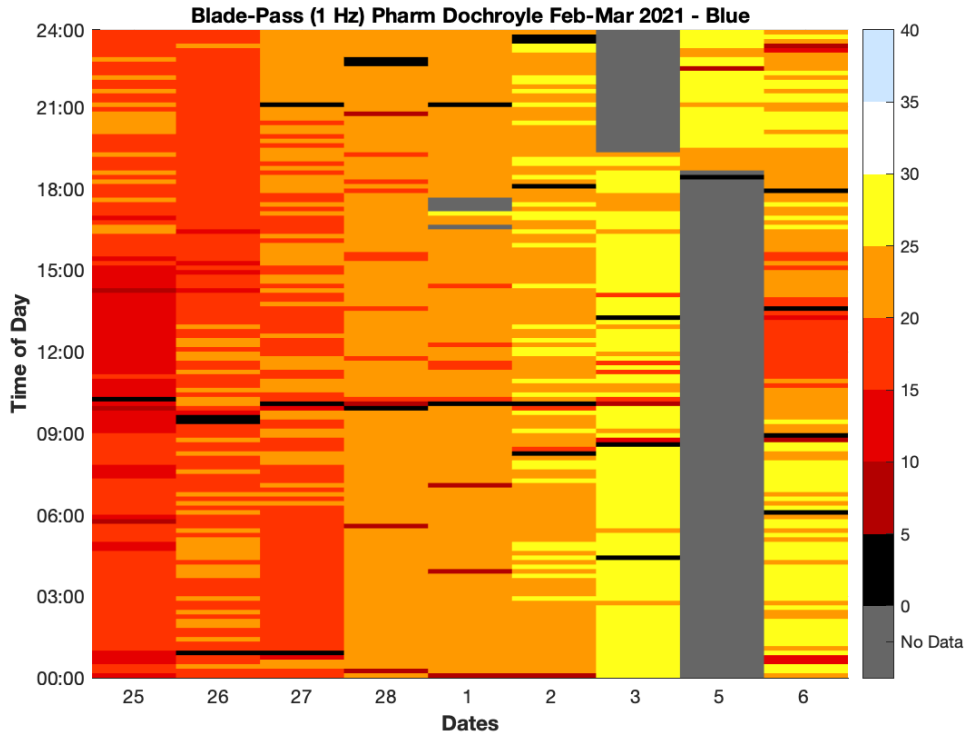


Figure 15: Blade-pass Harmonic Prominence Time-of-day for Blue channel from February 24th to March 6th, 2020. (Grey represents no measurement.)

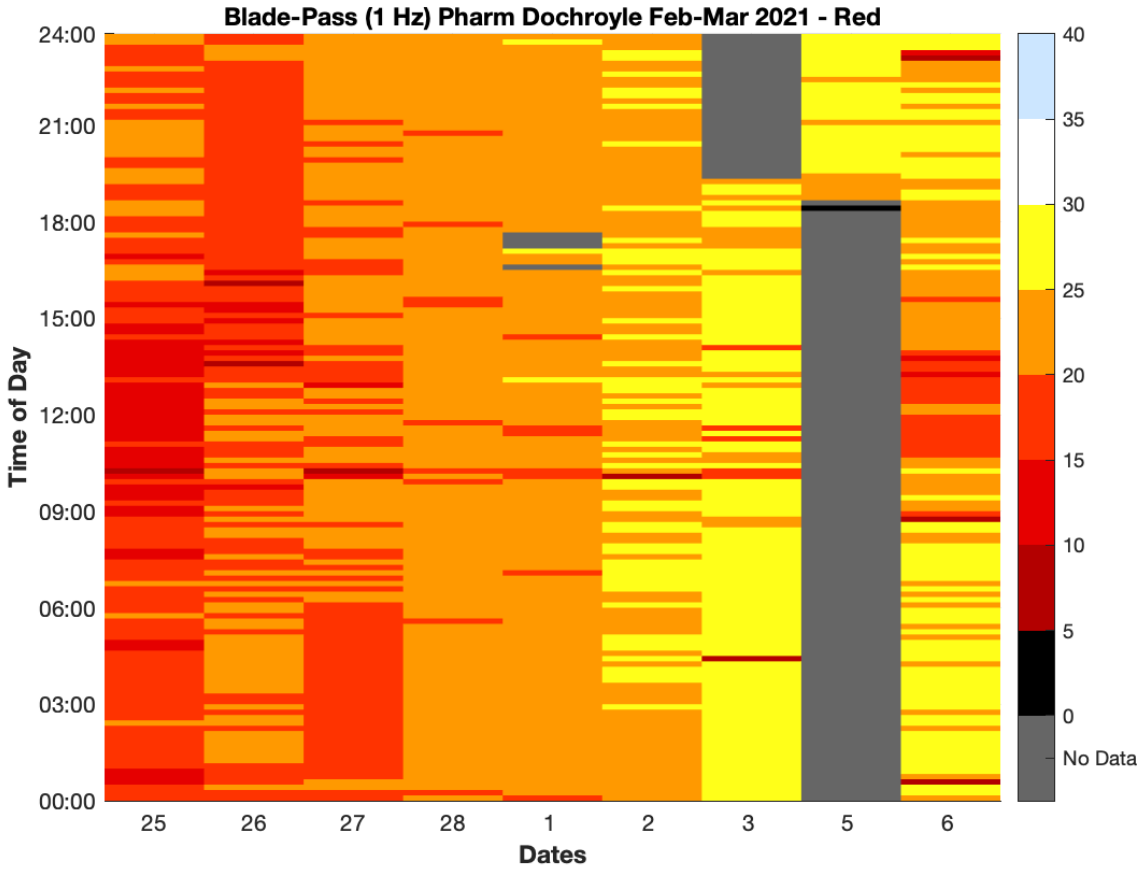


Figure 16: Blade-pass Harmonic Prominence Time-of-day for Red channel over the recording period. (Grey represents no measurement.)

7. Figures 15 and 16 show that the harmonic prominence levels ranged between 10 and 30 dB over almost all of the period February 26th to March 6th.

8. Almost all of the period from February 28th to March 2nd have harmonic prominence levels between 20 and 30 dB, while most of March 3rd shows harmonic prominence levels between 25 and 30 dB.

9. The harmonic prominence analysis was combined with the weather data from the Barrhill weather station to generate the following four harmonic prominence wind roses (see figures 17 and 18). The direction of each sector indicates the wind direction, the length represents the number of 10-minute samples and the colours represent the severity of the harmonic prominence in deciBels.

10. Barrhill weather station is roughly 3.7 km north of Dochroyle. Weather recorded there will be indicative of weather at, and between, the three surrounding wind power stations.

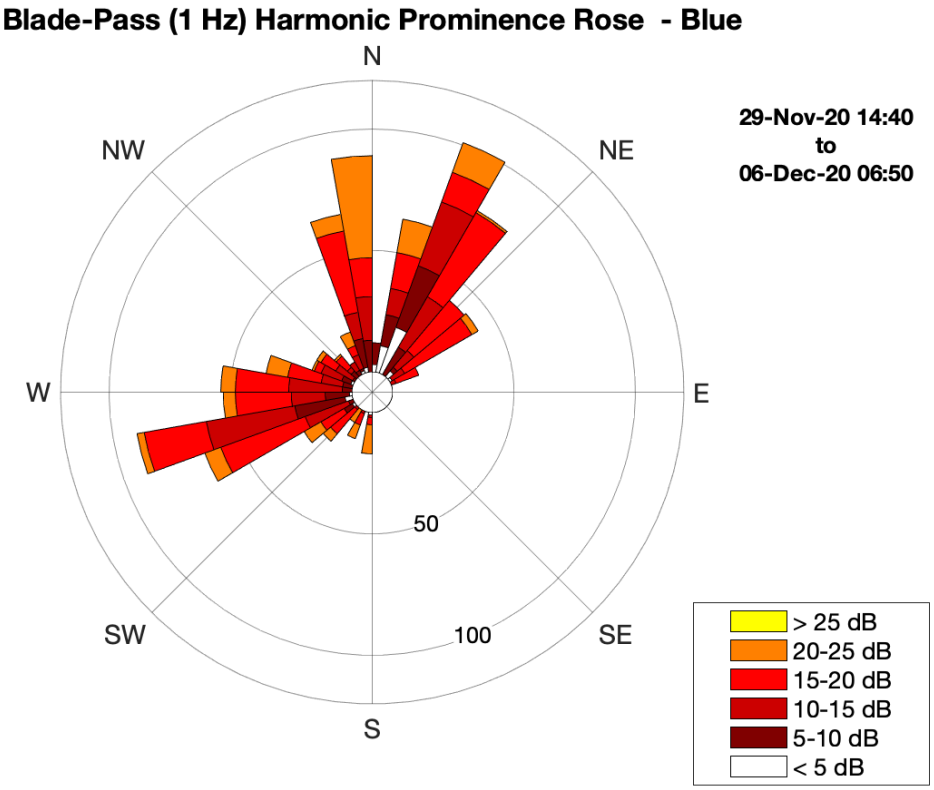


Figure 17: Harmonic Prominence Wind Rose for the Blue channel for November 29th to December 6th, 2020.

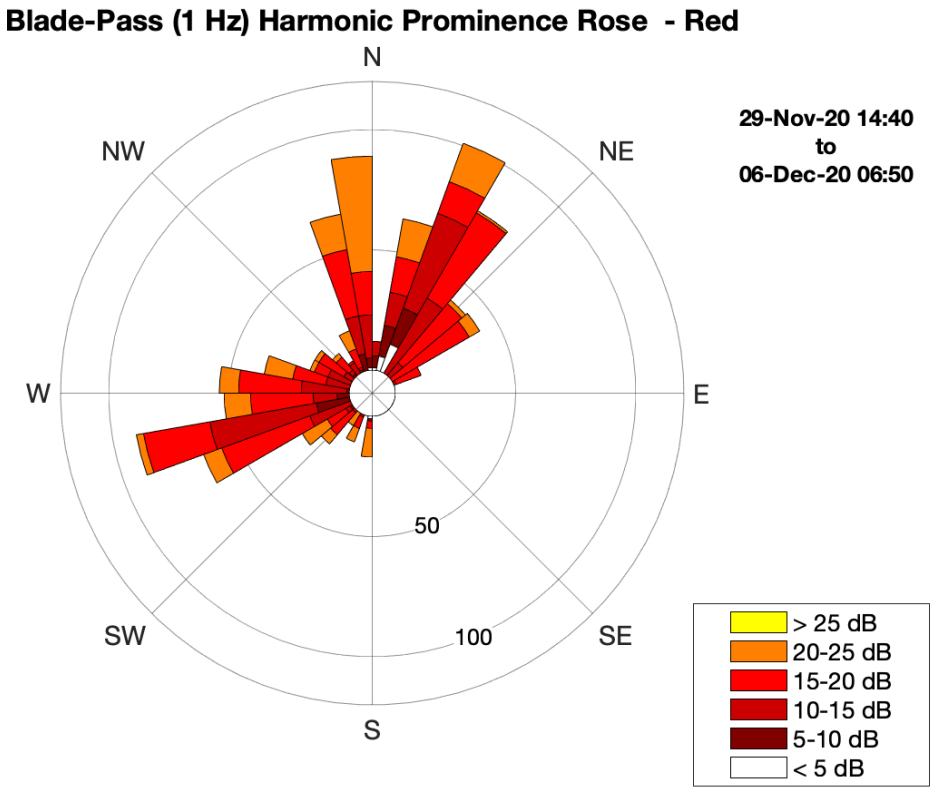


Figure 18: Harmonic Prominence Wind Rose for the Red channel for November 29th to December 6th, 2020.

11. The wind at the Barrhill station is seen to come mainly from the north and northeast during the recording period. None is seen to come from the east or southeast and almost none from the south.

12. The largest proportion of severe levels (orange, 20–25 dB) of harmonic prominence generally occur when the wind comes from the north or northeast, but this level is seen at lower proportions when the wind is from the northwest, west and southwest.

13. The Mark Hill wind power station is north-northeast of the Dochroyle residence, while the Arecleoch wind power station is to the west (see Figure 21). This provides support to the suggestion that the WTAS is mainly from the Mark Hill wind power station and less so from the Arecleoch wind power station. The highest proportion of severe harmonic-prominence levels appear to come from the direction of Mark Hill (north).

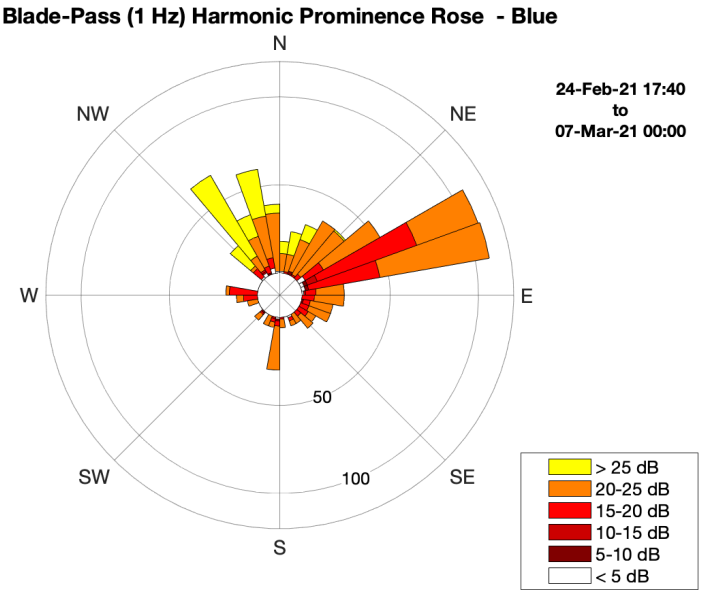


Figure 19: Harmonic Prominence Wind Rose for the Blue channel for February 28th to March 6th, 2021.

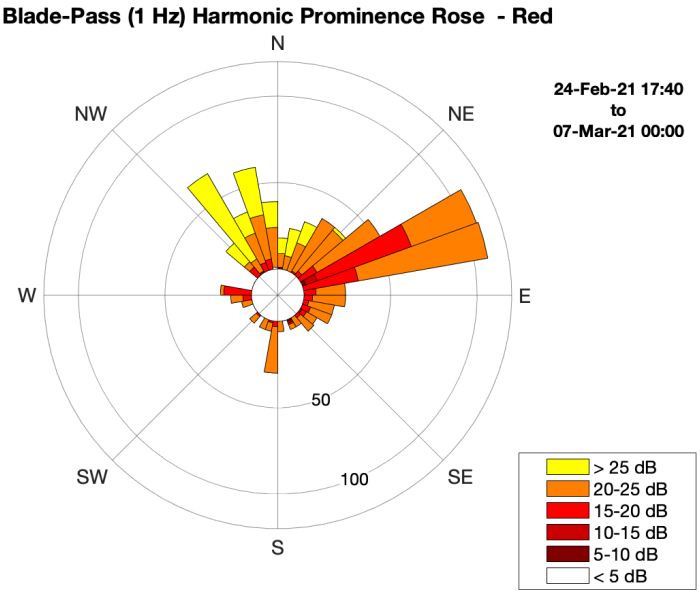


Figure 20: Harmonic Prominence Wind Rose for the Red channel f for February 28th to March 6th, 2021.

14. In this second set of recordings, taken in the spring, the overwhelming majority of harmonic prominence measurements are greater than 15 dB (red, orange and yellow sectors).

15. The most severe levels (yellow) occur when the wind is from the northwest through to roughly north, with the highest proportion of severe levels when the wind is from the northwest.

16. The Arecleoch wind power station is located to the west of the Dochroyle residence (see Figure 21), so this data suggests that the Arecleoch wind power station is most likely responsible for these levels of harmonic prominence.

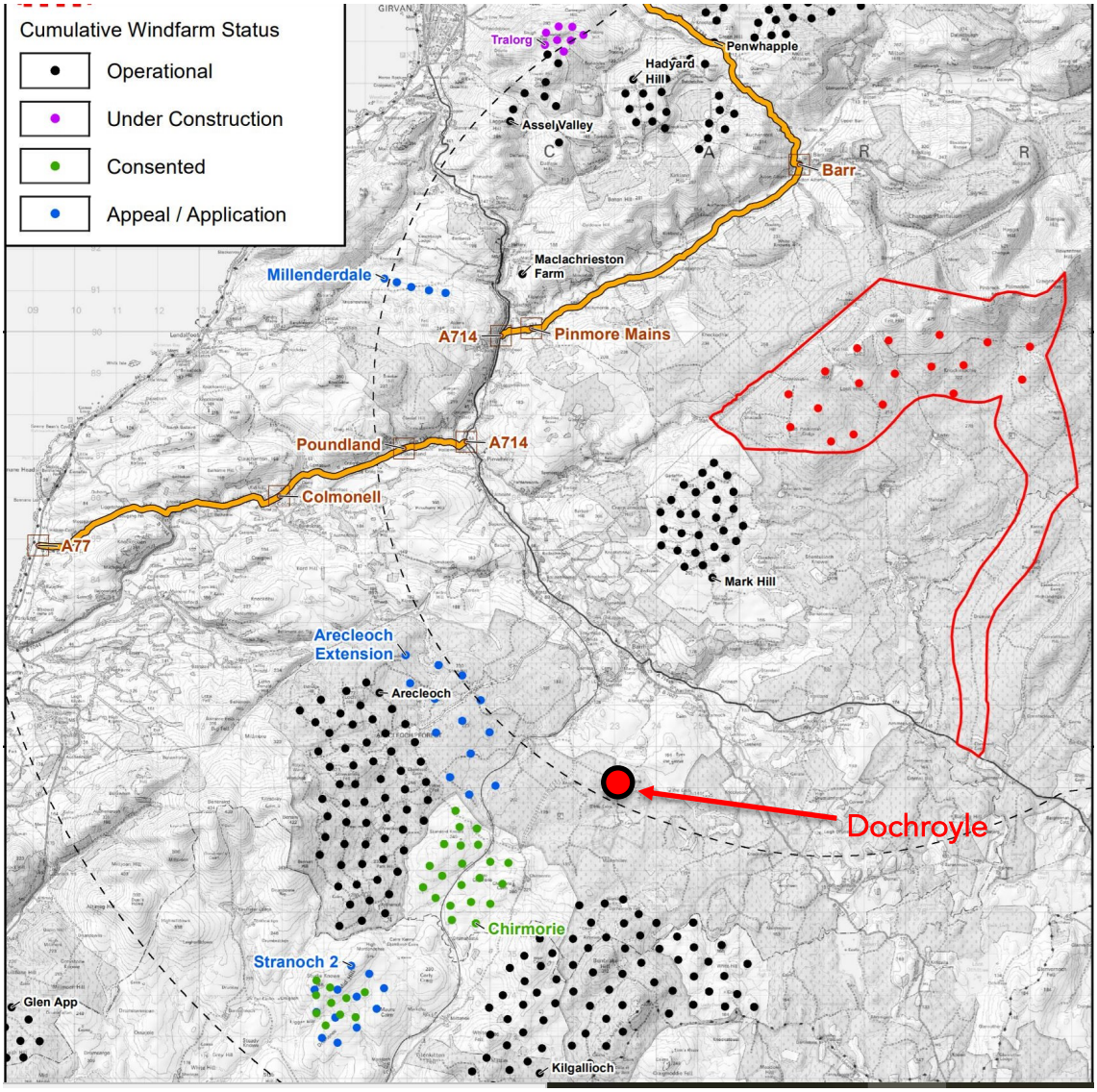


Figure 21: The Dochroyle residence and surrounding windfarms.

Correlation Analysis

1. The Spearman Rank Correlation method uses the order of ranking paired observations by each of the variables to determine the strength of the correlation. That is, if the order of observed pairs is the same when ranked by the first variable as when ranked by the second, then they are perfectly correlated. The sleep quality score was ranked smallest to largest where a score of 0 (0 cm) was the worst sleep and 10 (10 cm) was the very best sleep. The harmonic prominence was ranked smallest to largest according to its value in deciBels.

2. A value for the correlation coefficient of 0 will indicate that there is no correlation. A value of 1 indicates that there is a perfect correlation between the variables over all the observations. A value of -1 indicates a perfect anti-correlation, i.e., the rankings

are reversed between the variables. Values above about 0.7 (or below -0.7) indicate a strong correlation between the variables.

3. The significance of the result (how robust it is) is the probability of achieving a given value for the Spearman Rank Correlation coefficient if the distribution is random. It can be mapped onto the Gaussian (normal) distribution using the formula z = sqrt((n - 3)/1.06) * atanh(r), where z is the z-test value, n is the number of paired observations and r is the Spearman Rank Correlation coefficient. When there are less than 30 measurements, it is mapped on to the t-test distribution using the formula t = r*sqrt(n/(1-r^2)), where t is the t-test value. The test will be two-tailed as the null hypothesis is that there is no correlation between the variables, so either a positive or negative correlation would invalidate it.

4. The results of the Spearman Rank Correlation analyses are summarised in Tables 1 to 4.

Table 1: Sleep Quality vs Harmonic Prominence.

	Spearman Coefficient	t-test Value	Significance
Blue Channel	*-0.58*	*2.75*	*0.015*
Red Channel	*-0.57*	*2.75*	*0.015*

5. The correlation coefficient for both channels the same and show a moderate anti-correlation between the two variables, i.e., that sleep quality decreases with increasing harmonic prominence. These values suggest a **moderate anti-correlation**.

6. The significance probabilities are both below the p = 0.025 level that would indicate statistical significance. The suggestion of a moderate anti-correlation is **statistically significant**.

7. Bonferroni's correction was not applied as only one test was carried out for each bedroom.

Table 2: Temperature vs Harmonic Prominence.

	Spearman Coefficient	t-test Value	Significance
Blue Channel	*-0.40*	*0.76*	*0.505*
Red Channel	*-0.40*	*0.76*	*0.505*

8. The correlation coefficients for both channels indicate a **mild-to-moderate anti-correlation** between body temperature and harmonic prominence, i.e., increasing the harmonic prominence decreased the body temperature.

9. The significance probabilities are both much higher than the value of 0.025 for statistical significance. The mild-to-moderate anti-correlation is **not statistically significant**.

10. Statistical significance would not be expected in this case due to the very small number of samples, 5 only.

11. For the March 2021 recordings, values from a 5-point scale of "Noise perception" and "External vibration perception" were tested separately against mean harmonic prominence over the hour prior to the diary entry. The results are shown in Table 3 and Table 4.

Table 3: Noise Perception vs Harmonic Prominence.

	Spearman Coefficient	t-test Value	Significance
Blue Channel	*-0.43*	*1.06*	*0.34*
Red Channel	*-0.43*	*1.06*	*0.34*

12. The correlation coefficient for both channels the same and shows a moderate anti-correlation between the two variables, i.e., that perceived level of external noise decreases with increasing harmonic prominence. These values suggest a **moderate anti-correlation**.

13. The significance probabilities are both well above the p = 0.025 level that would indicate statistical significance. The suggestion of a moderate anti-correlation is **not statistically significant**.

Table 2: External Vibration Perception vs Harmonic Prominence.

	Spearman Coefficient	t-test Value	Significance
Blue Channel	*0.05*	*0.12*	*0.91*
Red Channel	*0.05*	*0.12*	*0.91*

14. The correlation coefficients for both channels indicate a **no correlation** between perceived level of external vibration and harmonic prominence.

15. The significance probabilities are both much higher than the value of 0.025 for statistical significance.

E. CONCLUSIONS

1. The recordings taken over the interval from November 29th, 2020 to December 6th, 2020 and from February 24th, 2021 to March 6th, 2021 were dominated by wind-turbine acoustic signature from the Arecleoch and Mark Hill wind power stations.

2. Harmonic prominences measured over the November-December interval were consistently between 10 and 25 dB in both measurement sites. They dropped below these levels only on December 4th. Levels consistently this high have never before been measured by the authors.

3. The majority of November 29th and December 1st had harmonic prominence levels over 20 dB.

4. Harmonic prominences measure over the February-March interval were even higher, being consistently between 20 and 30 dB on March 2nd and between 25 and 30 dB on March 3rd.

5. The wind at Barrhill weather station, and therefore also at the wind power stations and Dochroyle, over this period were predominantly from the northeast, north and southwest.

6. Most of the severe harmonic prominence levels (> 20 dB) occurred while the wind was from the north. The Mark Hill wind power station lies in this direction.

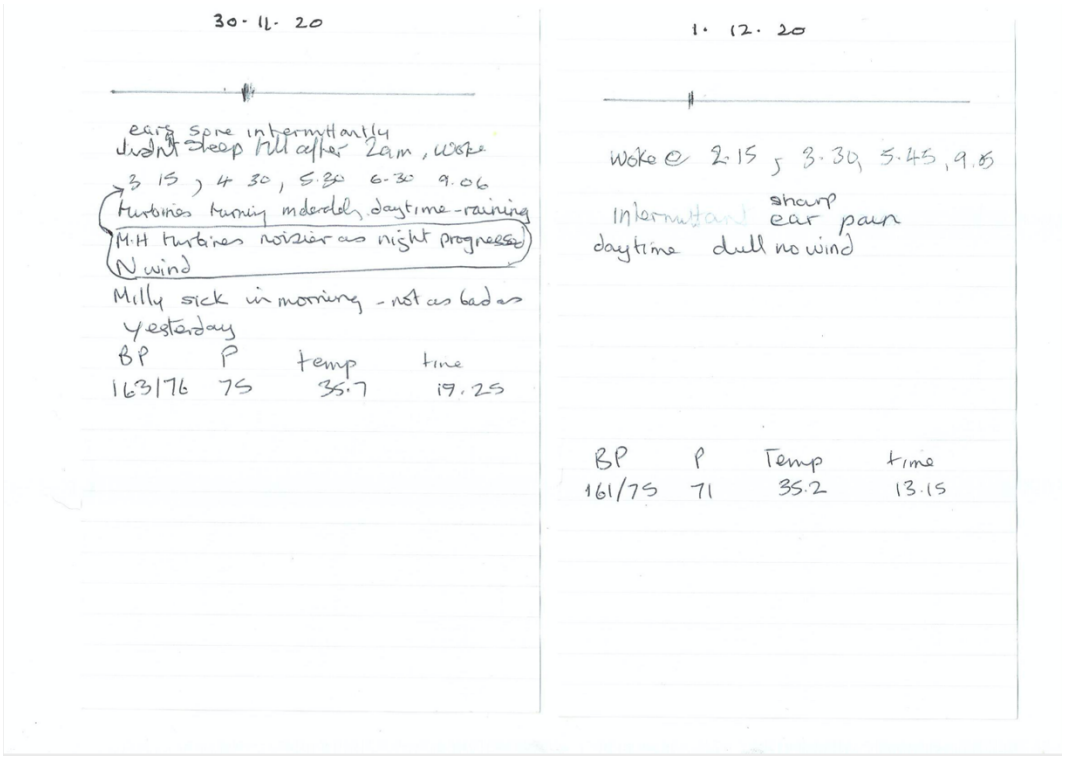
7. A Spearman Rank Correlation analysis indicated a moderate anti-correlation (-0.58) between quality of sleep (from the diary of one Dochroyle resident) and the average level of harmonic prominence in the hour prior. This was statistically significant at the $p = 0.025$ (two-tailed) level.

8. A further Spearman Rank Correlation analysis between body temperature and average harmonic prominence level over the hour prior indicated a mild-to-moderate anti-correlation (-0.40) but was based on only 5 measurements and so cannot be considered as statistically significant.

F. APPENDICES

Appendix 1

Sleep diaries for Pat Spence, Dochroyle



30. 11. 20

ears sore intermittantly
didn't sleep till after 2am, woke
3 15) 4 30, 5.30 6.30 9.06
Turbines turning moderately daytime - raining
M.H turbines noisier as night progresses
N wind
Milly sick in morning - not as bad as yesterday

BP	P	temp	time
163/76	75	35.7	19.25

1. 12. 20

woke @ 2.15) 3.30, 5.45, 9.05
intermittant sharp ear pain
daytime dull no wind

BP	P	Temp	time
161/75	71	35.2	13.15

2. 12. 20

woke at 5.45 & 7.45
Sunny no wind
12. 58 sharp ear pain

BP	P	Temp	time
155/83	70	36.4	13.50

3. 12. 20

woke 2am 4am & 5.05 am
severe ear pain T. 29. 10.30 & 12.58

dull still cold

BP	P	temp	time
175/85	73	35.8	14.05

4.12.20

Slept about 2am – 6.45
stormy wind – no turbines
Woken 8.27 (turbines thumping) from
weird dream – ~~woke~~
Snow! – melted quickly
weak sun no wind
concentration poor during the day

BP	P	temp	time
160/86	74	35.7	14.20

5.12.20

Slept 2 – 4.20 next woke 8.30
cold dull still

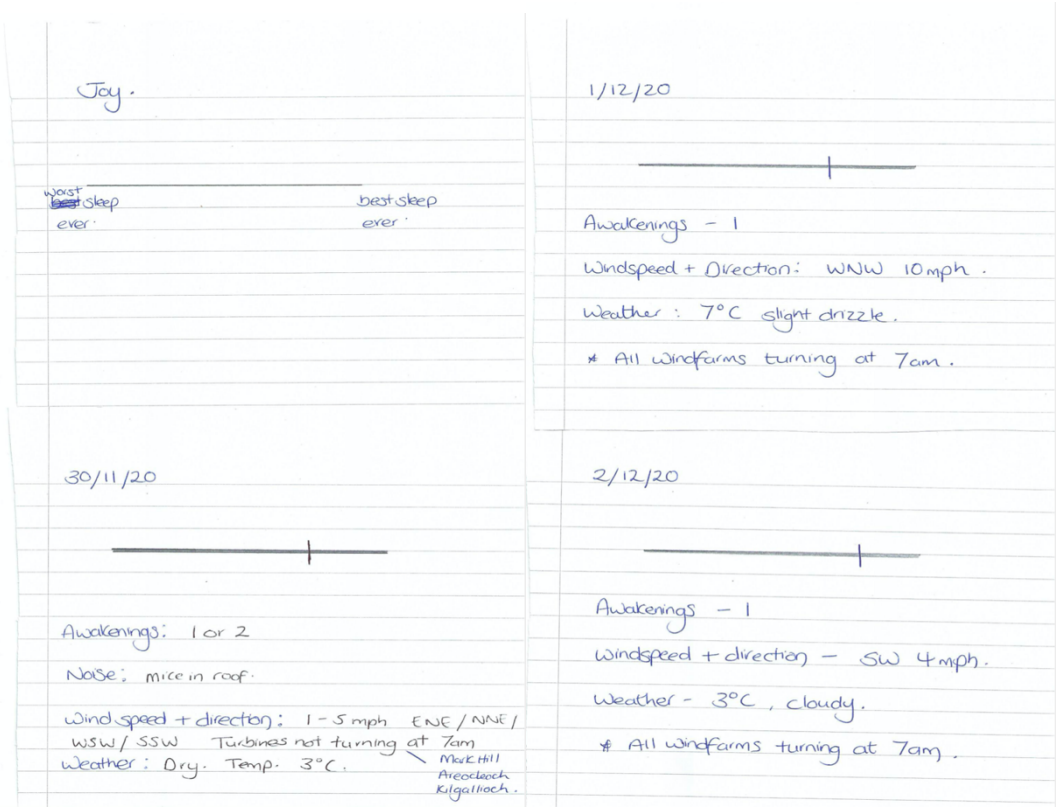
6.12.20

woke at 4.30 8.30 10.15
V. hard frost – no wind

BP	P	temp	time
165/80	81	35.6	13.25

Appendix 2

Sleep diaries for Joy and Russ, Shallochwell



Joy.

worst sleep ever.

best sleep ever.

30/11/20

Awakenings: 1 or 2

Noise: mice in roof.

Wind speed + direction: 1 - 5 mph ENE / NNE / WSW / SSW Turbines not turning at 7am Mark Hill Areodoch Kilgallioch.

Weather: Dry. Temp. 3°C.

1/12/20

Awakenings - 1

Windspeed + Direction: WNW 10mph.

Weather: 7°C slight drizzle.

* All windfarms turning at 7am.

2/12/20

Awakenings - 1

Windspeed + direction - SW 4mph.

Weather - 3°C, cloudy.

* All windfarms turning at 7am.

3/12/20

Awakenings - 0

Noise - wind gusts.

Windspeed + direction: 16mph NNW

Weather: 3°C, snow.

* all windturbines turning.

4/12/20

Awakenings - 1

Windspeed + Direction. 11mph N.

Weather - cloudy 4°C. + dry.

* all turbines turning.

5/12/20

Awakenings 2 - (dogs barking).

Windspeed + direction - 5mph N.

Weather - -2°C, dry + clear.

* all wind farms turning.

6/12/20

Awakenings - lots.

Windspeed + direction: 5mph N.

Weather: -2°C, dry.

All turbines turning.

30/11/20 Russ.

Awake / got up approx 3:30am.

1/12/20

Awake + got up approx 3:30am.

2/12/20

Awake + got up approx 3am.

3/12/20

4/12/20

5/12/20

* NOT HERE'

6/12/20

Appendix 3

Sleep Diary for A. Rofe, ?????