IARO
INTERNATIONAL ACOUSTICS RESEARCH ORGANIZATION

ANNEX A

Technical Background for Laypersons

(Annexed to IARO REPORT No. IARO23-C1)

December 2023

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.

Contacts:

IARO, 37 Weston Ave, Palmerston North, 4414, New Zealand

Tel: +64 21 033 6528

Email: HuubBakker@smart-technologies.co.nz

This Annex A accompanies the December 2023 IARO Report No. IARO23-C1—High-Resolution Infrasonic and Low-Frequency Sound Recordings conducted at REDACTED, Scotland in 2022 and 2023.

The goal of this Annex is to provide the IARO Report readers with a more substantial background on: The Current State of Affairs in the U.K. regarding onshore wind power plants (Section 1), The SAM Technology (Section 2), the Types of Analyses obtained with the SAM Technology (Section 3).

Authors of this Report *(alphabetical)*

Mariana Alves-Pereira, Ph.D., Lusófona University, Lisbon, Portugal

Huub Bakker, Ph.D., IARO, Palmerston North, New Zealand

Susan Crosthwaite, Citizens' Initiative UK, Scotland

Rachel Summers, IARO, Palmerston North, New Zealand

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ACRONYMS AND VARIABLES

Table 1. Acronyms and Variables used in this Report

BPF	Blade-pass Frequency
CSI-ACHE	Citizen Science Initiative for the Acoustical Characterization of Human Environments
IWT	Industrial Wind Turbine
P_{peak}	Peak Harmonic Prominence
RES	Renewable Energy Systems
SLM	Sound Level Meter
SPL	Sound Pressure Level
Wdir	Wind Direction
WPP	Wind Power Plant
Wsp	Wind Speed
WTAS	Wind Turbine Acoustic Signature

1. CURRENT STATE OF AFFAIRS IN THE U.K. REGARDING ONSHORE WIND POWER PLANTS

I. Wind Power Plants and their Neighbouring Communities

1. It may be surprising to those reading this report that, all over the world, including the UK:

a. Citizens living in the vicinity of onshore wind power plants (WPPs) have been complaining of adverse health effects, also observed in pets and livestock.

b. Citizens living in the vicinity of onshore and offshore WPPs have formed small, grass-roots groups to confront the 'wind industry.'

c. Numerous legal proceedings are ongoing, initiated by private citizens, or by groups of private citizens, against the 'wind industry.'

d. Many of the ongoing and concluded legal proceedings are subjected to non-disclosure agreements, or gag orders.

2. In the UK, situations where residential communities oppose WPPs are not new, and have been ongoing for three decades, since the operation of the first wind turbines in 1991 at Delabole in Cornwall—hub height: 32m, blade length: 17 m. For comparison, in 2021, the Industrial Wind Turbines (IWTs) of the Arecleoch WPP in Scotland have a hub height of 83 m, and a blade length of 69 m. The 14 IWTs installed at Blary Hill WPP have a hub height of 65 m and a blade length of 45 m. See Fig. 1, reproduced from industry literature.

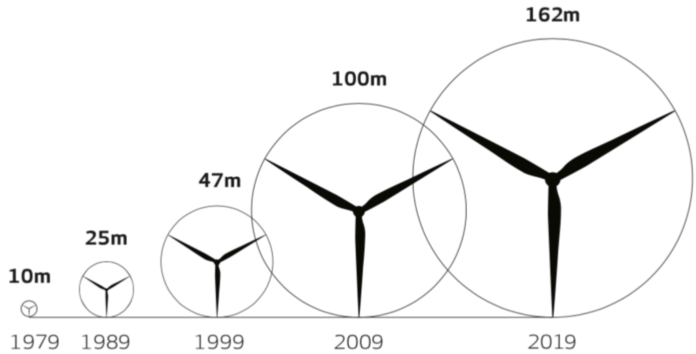

Figure 1. Evolution of the size of wind turbine rotor blades[1].

3. In addition to the stroboscopic effect (which, in the sole case of wind turbines, is termed 'shadow flicker') and the decreased visual amenity, IWTs also produce 'noise.'

4. A part of the 'noise' produced by IWTs is of a unique type, that is not properly contemplated in current assessment guidance: trains of pulsed infrasonic peaks (sometimes reaching more than 20 dB over environmental background level) and non-trivial levels of low frequency noise.

5. The immediate and long-term effects of this unique type of 'noise' on human health are, for the most part, not investigated[2].

II. ETSU-R-97

6. In the U.K., the document that regulates WPP noise is ETSU-R-97[3]. The 175-page document, titled "The assessment & rating of noise from wind farms," has an opening statement which is fully transcribed below:

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[1] Vestas Wind Systems A/S, 2019. "EnVentus Platform" Brochure. https://www.vestas.com/en/products/enventus-platform/enventus-platform

[2] Redacted.

[3] ETSU-R-97: The assessment and rating of noise from wind farms. The Working Group on Noise from Wind Turbines, Final Report September 1996. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/49869/ETSU_Full_copy__Searchable_.pdf

This report was drawn up under the direction of the Noise Working Group. While the information contained in this report is given in good faith, it is issued strictly on the basis that any person or entity relying on it does so entirely at their own risk, and without the benefit of any warranty or commitment whatsoever on the part of the individuals or organisations involved in the report as to the veracity or accuracy of any facts or statements contained in this report. The views and judgements expressed in this report are those of the authors and do not necessarily reflect those of ETSU, the Department of Trade and Industry or any of the other participating organisations [4].

7. It might now be interesting to list the people and entities who knowingly co-signed a document of (self-acknowledged) questionable veracity and dubious accuracy[5]:

Table 1. Members of the Noise Working Group

Mr R Meir, Chairman	DTI
Dr M L Legerton, Secretary	ETSU
Dr M B Anderson	Renewable Energy Systems
Mr B Berry	National Physical Laboratory
Dr A Bullmore	Hoare Lea and Partners
Mr M Hayes	The Hayes McKenzie Partnership
Mr M Jiggins	Carrick District Council
Mr E Leeming	The Natural Power Company Ltd
Dr P Musgrove	National Wind Power Ltd
Mr D J Spode	North Cornwall District Council
Mr H A Thomas	Isle of Anglesey County Council
Ms E Tomalin	EcoGen Ltd
Mr M Trinick	Bond Pearce Solicitors
Dr J Warren	National Wind Power Ltd

8. _Question_: Who represented the medical community?

4 ETSU-R-97, Page 0

5 At least two of the commercial enterprises represented in this Working Group are still closely involved in current wind power plant planning procedures: Hayes McKenzie Partnership and Hoare Lea and Partners.

9. If no medical expertise was relied upon, why is ETSU-R-97 presumed to incorporate the protection of Public Health against IWT noise?

10. The answer to this question becomes obvious in the first paragraph of the ETSU's Executive Statement, transcribed below (our bold):

> *This document describes a framework for the measurement of wind farm noise and gives indicative noise levels thought* ***to offer a reasonable degree of protection*** *to wind farm neighbours,* ***without placing unreasonable restrictions on wind farm development or adding unduly to the costs and administrative burdens on wind farm developers*** *or local authorities. The suggested noise limits and their reasonableness have been* ***evaluated with regard to regulating the development of wind energy in the public interest.*** *They have been presented in a manner that* ***makes them a suitable basis for noise-related planning conditions or covenants within an agreement between a developer of a wind farm and the local authority*** *(Executive Summary, page iii).*

11. In conclusion, ETSU-R-97 does not cover health effects that may arise due to WPP noise exposure[6].

III. Infrasound Considered Non-Existent by Governmental Authorities

12. Considering the antiquity of ETSU-R-97 (originally established in 1997), in 2021 the U.K. Government's Department of Business, Energy and Industrial Strategy (DBEIS) launched a "Scoping review of current onshore wind turbine noise assessment guidance" with the following stated purpose:

> *The purpose of the review is to determine whether the guidance adequately ensures that wind farm turbine noise is managed effectively and consistently in line with current Government policies on noise (…), accounts for contemporary technological and acoustical developments, and (if not), what updates may be necessary to achieve this* [7].

[6] Redacted.

[7] In: Scientific Commentary on the UK Government's Department of Business, Energy and Industrial Strategy (DBEIS) "Scoping review of current onshore wind turbine noise assessment guidance." Document number IARO21-6, December 2021. The DBEIS site regarding the "Scoping Review" has since been taken down. IARO Report No. IARO21-6 is available upon request.

13. However, "Government policies on noise" were to only include those associated with "Amplitude Modulation" and "Tonality"—two features associated with 'noise' emitted by wind turbines, both of which imply (exclusively) the existence of audible disturbances[6].

14. Notably, there is no entry for "Infrasound" nor for "Low Frequency Noise[7].

15. The item associated with "Amplitude Modulation" may cover some aspects of the audible, low frequency noise emissions because it is related to the "whooshing" and "swishing" sounds emanating from wind turbines (see Para. 45-49 and Fig. 14).

16. Subsequent to the 2022 DBEIS Scoping Review, WSP (a professional services firm) published: "Report for UK government: A review of noise guidance for onshore wind turbines," dated 10 February 2023[8]. The Independent Noise Working Group (INWG, a multidisciplinary team independent of industry and government) published: "INWG Analysis of WSP Report titled: 'A review of noise guidance for onshore wind turbines,' dated 15 April 2023[9]. The exploration of the contradictory views provided in these two reports is beyond the scope of this Annex and corresponding Report.

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8 LinkedIn Announcement of the WSP Report, dated 10 February 2023: https://www.linkedin.com/pulse/publication-wsp-report-uk-government-review-noise-guidance-lotinga. Full WSP Report dated 31 May 2023: https://www.wsp.com/en-gb/insights/wind-turbine-noise-report.

9 Full See INWG Report, dated 15 April 2023: https://inwg.org.uk/wp-content/uploads/2023/05/INWG-Analysis-of-WPS-Report-15-April-2023.pdf

2. THE SAM TECHNOLOGY

17. The SAM Technology arose with the scientific necessity to quantify the environmental soundscape as to it infrasonic and lower frequency components.

18. Sound level meters (SLM) commonly available on the market are not designed to assess any parameters that are not related to those used by established legislation, namely (in the U.K.), ETSU-R-97 and the *Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise*, published in 2013 by the Institute of Acoustics, UK.

19. The SAM Technology—including the microphones, EV05 sound card, calibrator, computer, and software—is **not a sound level meter**. While the SAM Sentinel software provides the functionality of a SLM, it is not class typed and carries no certificate for this functionality.

20. The SAM Technology provides research-grade recording where the focus is on discovery and analysis rather than compliance testing, which *would* require class typing to acoustic standards.

21. The manufacturers of the Primo microphone capsules provide test results indicating that the capsules have a level response between roughly 0.5–5000 Hz (see Fig. 2).

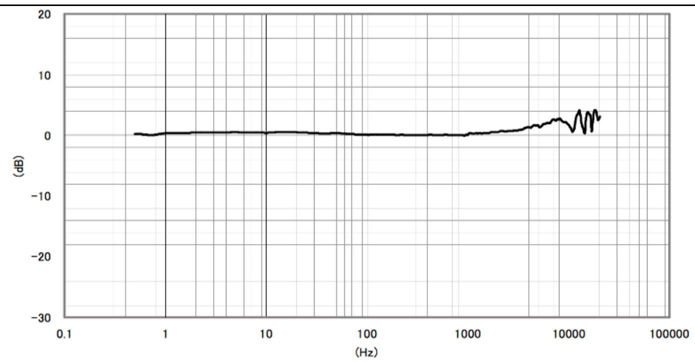


Figure 2. Manufacturer's specification for the Primo microphone capsule used in both the SAM Mk1 and SAM Mk2 systems.

22. The EV05 sound card has been tested against Class 1 SLMs and shown to have a high degree of linearity down to roughly 0.2 Hz. Only SLMs with specialist, infrasound-rated microphones can be used for comparisons below 20 Hz and, even then, the SLMs may only report levels down to several Hertz.

23. The recordings made by the SAM technology are calibrated by including a 1000-hertz, 94-decibel tone from a Class 1 calibrator. Analysis of calibration tones recorded by a Mk1 system over several years indicates that the EV05 sound card maintains an uncalibrated accuracy of roughly ±2 dB.

24. Frequency analyses of the recordings are performed using narrow-band filters 1/36 of an octave wide. These filters meet the requirements of Class 0 filter banks for both ANSI® S1.11-2004 and IEC 61260:1995.

25. As a result of these specifications, the SAM recording technology, and subsequent analysis software, can produce analyses sufficient to determine the characteristics and sound pressure levels of the acoustic environment to a similar level of accuracy as recordings made by SLMs. They do not carry the type certification required for compliance testing.

26. The SAM technology allows for the high-resolution study of environmental soundscape. As shall be seen in the following sections, this high-resolution analysis reveals acoustical phenomena that would otherwise remain undetected—specifically, if the low-resolution methodologies imposed by U.K. (and other international) legislation and recommended practices are implemented. Table 2 summarizes the major differences between both methodologies which will be explored more fully below (see **Section 3. IX. Differences Between IARO Analysis and Legislated Methodologies**).

Table 2. Summary of Differences between IARO Analyses and other Analyses

Parameter	IARO	Other
Frequency resolution	1/36th of an octave	1/3rd of an octave
Time resolution	Second by second	10-minute averages*
Frequency-weighting	None (Unweighted)	A-, C- or G-weighting

*1-minute and 10-second averages are also included in some situations.

27. While the implications on Public Health are profound, these are covered in a separate Report[6].

3. TYPES OF DATA ANALYSES

28. The following sections explain the different types of data analyses currently used by IARO scientists. The examples included herein are based on date recorded in several countries, and not merely at REDACTED in Scotland. The two most common analyses are the Sonogram and the Harmonic Analysis.

I. Sonograms

29. Figure 3 shows an example of a sonogram that will be used as a template to introduce the visual features that are important for reading a sonogram (Figs. 4-9).

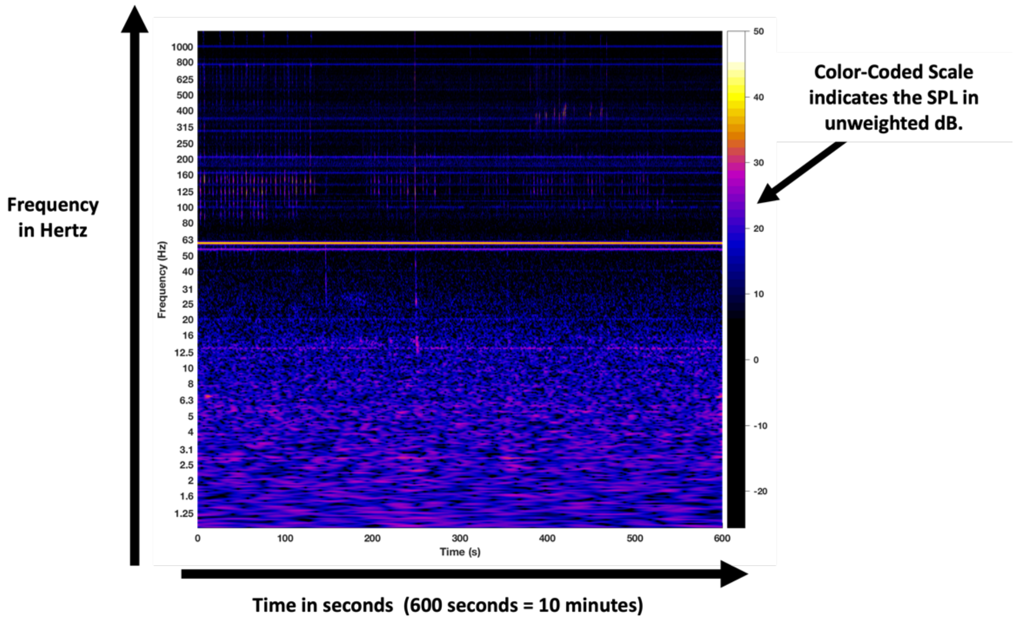


Figure 3. Example of a sonogram recorded in a bedroom during the early morning hours. Sonograms have frequency values (in Hertz) along the vertical, Y-axis and time values (in seconds) along the horizontal, X-axis. The colour-coded scale indicates the sound pressure level (SPL, in dB) present at each second (for a period of 600 seconds or 10 minutes) and at each frequency value, in a 1/36th octave scale.

30. The classical segmentation of the acoustic spectrum is shown in Figure 4.

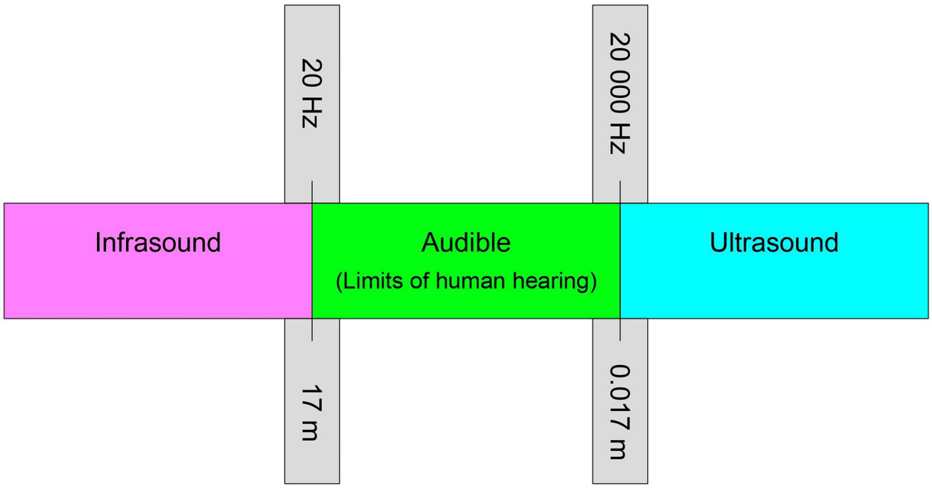


Figure 4. Classical segmentation of the acoustic spectrum. Sound that is considered audible occurs within the 20 to 20 000 Hz range, corresponding to wavelengths between 17 m and 1.7 cm (respectively). Infrasonic acoustic events, below 20 Hz, are considered inaudible and occur with wavelengths larger than 17 m. Ultrasound, at frequencies above 20 000 Hz, is also considered inaudible and is beyond the scope of this report.

31. The classical segmentation shown in Figure 4 is transcribed to the sonogram shown in Figure 5.

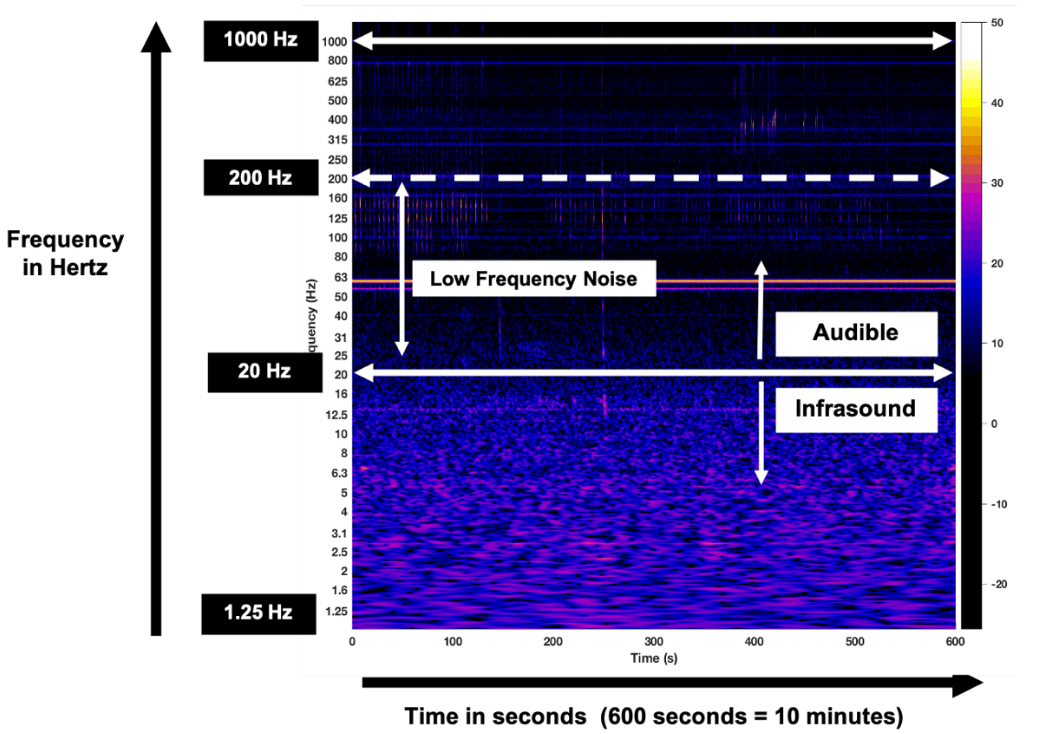


Figure 5. The classical segmentation of the acoustic spectrum is indicated: Infrasound below 20 Hz and Audible above 20 Hz. Here, the lower frequency components are also included—currently considered as the frequency range between 20 Hz and 100 or 200 Hz, depending on the authors.

32. The lower limiting frequency of data captured by the SAM system is 0.5 Hz. In the IARO analyses, the upper limiting frequency is 1000 Hz, although the SAM system captures data between 0.1 Hz and 10,000 Hz (see Fig. 2 showing the frequency-response curve of the SAM microphones).

33. Figure 6 points out the use of the colour-coded scale to evaluate the dB-level of the (most prominent) continuous tones, occurring at approximately 30 and 40 dB. These appear above the 20 Hz cut off which means they are (potentially) audible.

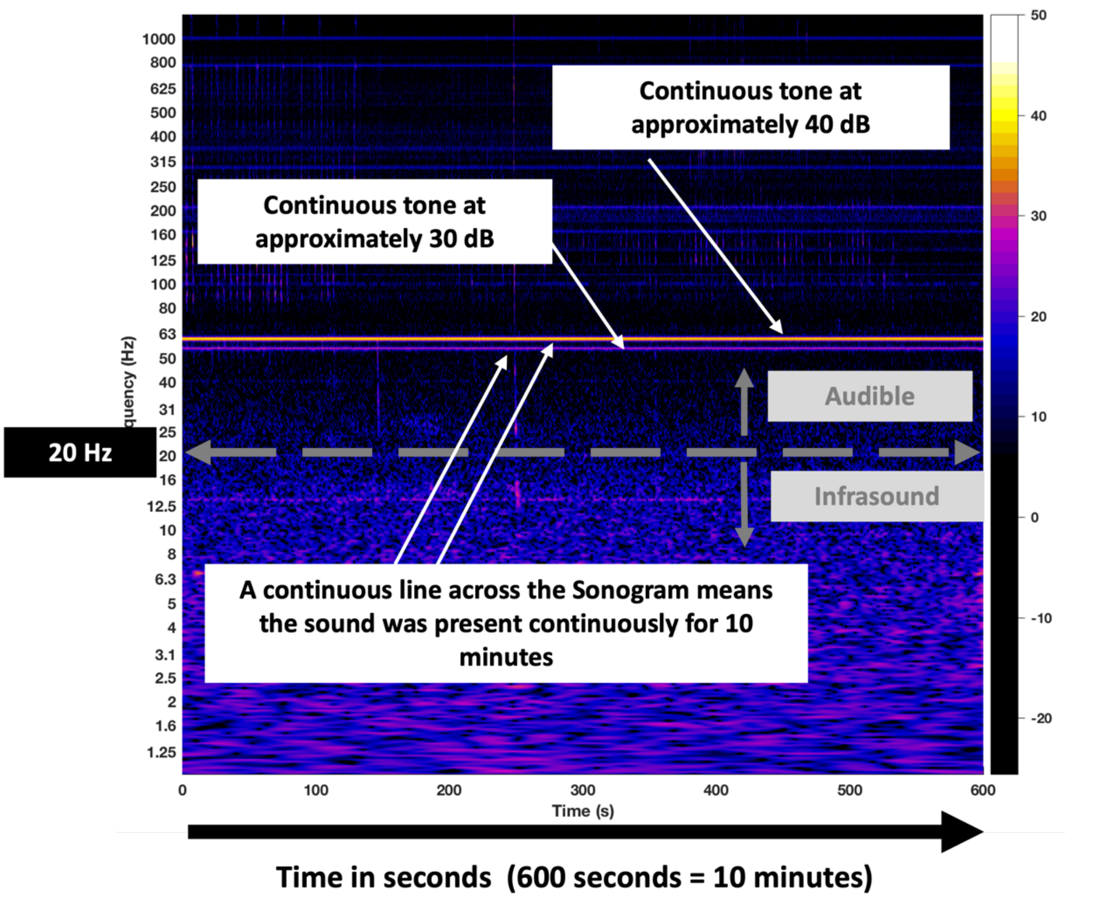


Figure 6. Sonograms present continuous tones as straight lines across the entire image. In this example, these continuous tones, at approximately 30 dB (purple line) and at 40 dB (yellowish line) exist during the entire 10 minutes of the sample.

34. Figure 7 shows the difference between momentary sounds (vertical lines) that are, in this example, associated with snoring, and continuous sounds (horizontal lines) which, in this example reflect in the "hum" of electrical mains.

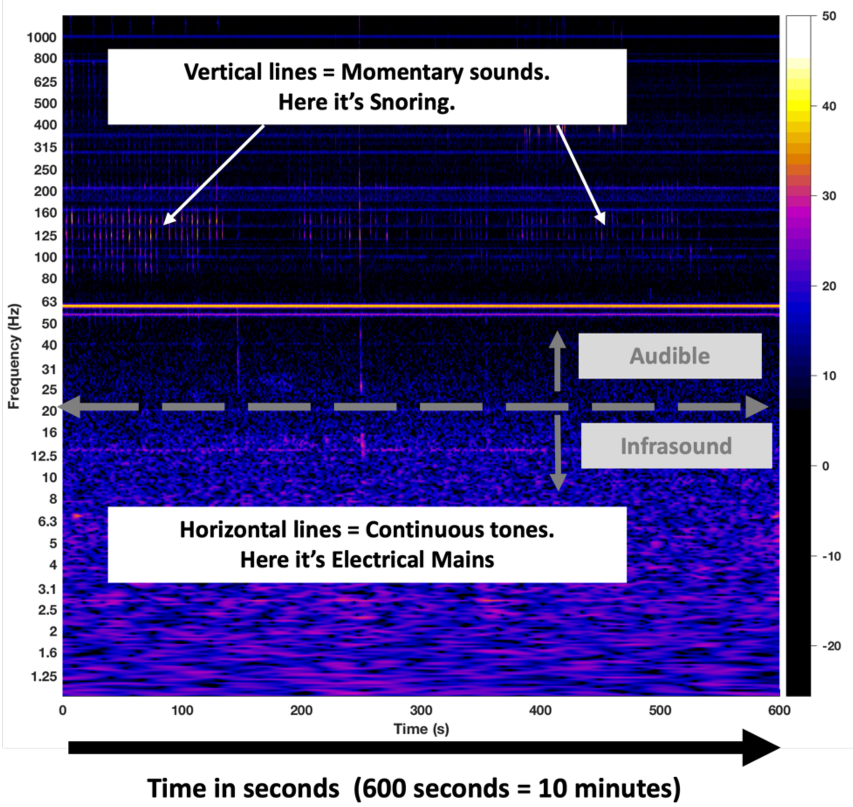


Figure 7. Sonograms present momentary sounds as vertical lines, as shown here and that represent sounds associated with snoring. These sounds are within the 20-30 dB range, as indicated by the colour of the vertical lines.

35. Figure 8 shows an example of a Wind Turbine Acoustic Signature (WTAS).

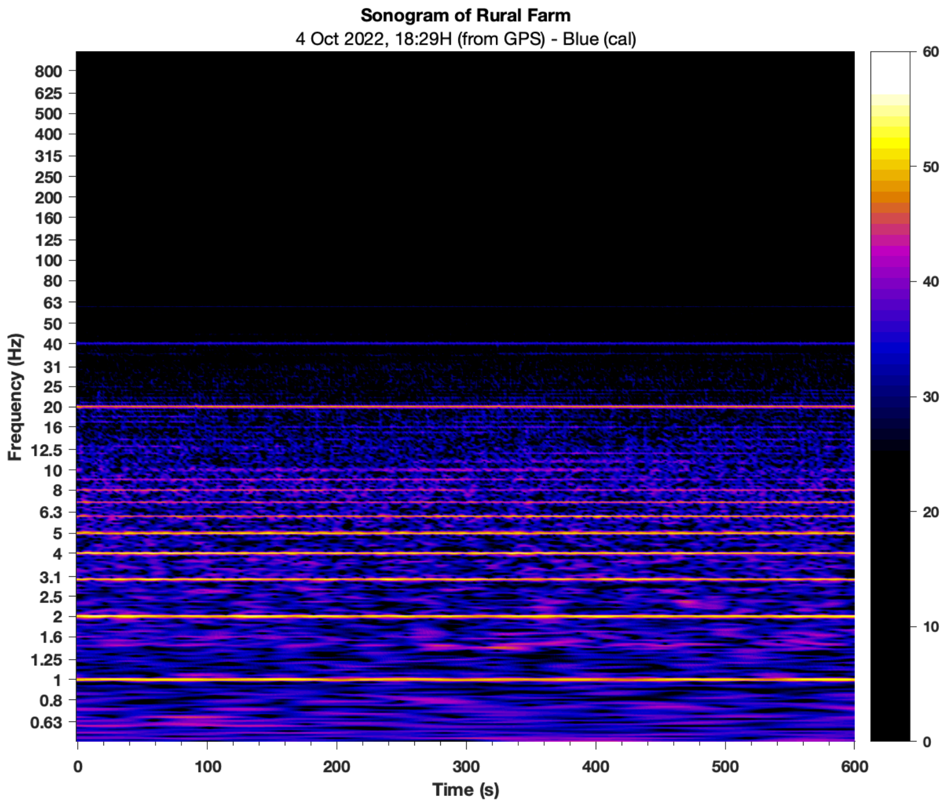


Figure 8. Sonogram showing the existence of WTAS (wind turbine acoustic signature). This 10-minute segment was captured at farm in rural Scotland (18:29H, on 4 Oct 2022, microphone in bedroom). The average windspeed during the hour in which this 10-minute segment was recorded was 3.0 m/s (11 km/h) from the southwest (Wsp = 3.0 m/s (11 km/h), Wdir = SW). The horizontal lines evidence of a train of pressure pulses, one of which is emitted from a turbine each time a blade passes a particular part of its rotation, e.g., the tower.

36. Figure 9 details features seen in Figure 8, and which are important for being able to read a sonogram.

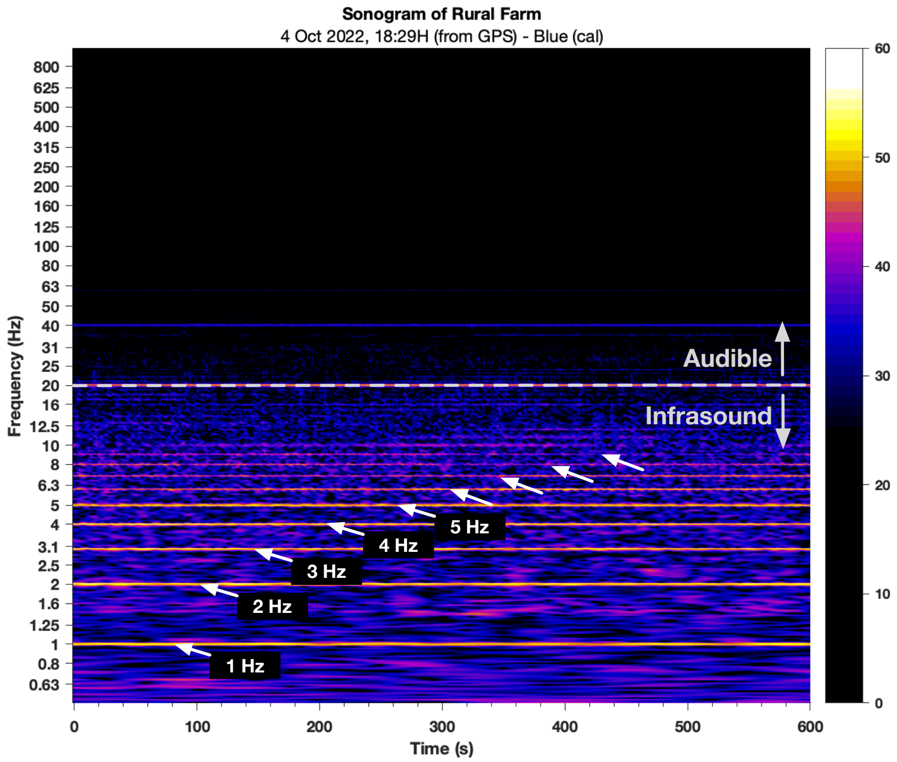


Figure 9. Each small white arrow points to one of the continuous horizontal lines that appear over the entire 10-minute segment. Each horizontal line is occurring at specific infrasonic frequencies, as indicated in the black boxes (and also on the YY-axis labelled "Frequency"). Noticeably, each of these lines is equally spaced from each other (see Para. 37). Collectively, these horizontal lines constitute the WTAS. The first five horizontal lines (1-5 Hz) are colour-coded at approximately 50 dB, with the remaining lines (6-10 Hz) color-coded at around 40 dB. There is also a 20-hertz harmonic series showing tones at 20 Hz (visible in Fig. 8 at about 40 dB), 40 Hz, and 60 Hz (very faint). Within the audible range of the frequency spectrum (above 20 Hz), there are no significant acoustic events, except for the continuous line at 40 Hz, color-coded at approximately 30 dB.

37. Each of the horizontal lines seen in Figure 9 are equally spaced from each other: 1 Hz, 2 Hz, 3 Hz, 4 Hz, 5 Hz, 6 Hz, 7 Hz, 8 Hz, 9 Hz and 10 Hz. Mathematically, this is called a harmonic series where each frequency value is an integer value above the fundamental frequency (F_0) which, in this case, is 1 Hz. See Table 3 for clarification.

Table 3. Harmonic Series: construction and referral to Fig. 8.

Level (dB)*	Frequency (Hz)	Order of the Harmonic
50	1	Fundamental Frequency = F_0 (Lowest horizontal line in sonogram)
	2	Second (1 x 2)
	3	Third (1 x 3)
	4	Fourth (1 x 4)
	5	Fifth (1 x 5)
40	6	Sixth (1 x 6)
	7	Seventh (1 x 7)
	8	Eighth (1 x 8)
	9	Ninth (1 x 9)
	10	Tenth (1 x 10)

* Level is in unweighted dB (see IX. Differences Between IARO Analyses and Legislated Methodologies).

38. Figure 8 shows a harmonic series with a fundamental frequency of 1 Hz. This corresponds to the infrasonic acoustic output of Industrial Wind Turbines (IWT) that have a Blade-Pass Frequency (BPF)[10] of 1 Hz.

II. Harmonic Analysis

39. The data captured with the sonogram can also be viewed in a different manner, called a Spectrogram. Harmonic Series Analyse are based on the Spectrogram. Figure 10 shows the Harmonic Series Analysis based of the spectrogram that corresponds to the sonogram shown in Figure 8.

[10] Blade-Pass Frequency (BPF) is the number of times a rotor blade passes a fixed point, e.g. the tower, per second (see Para. 83).

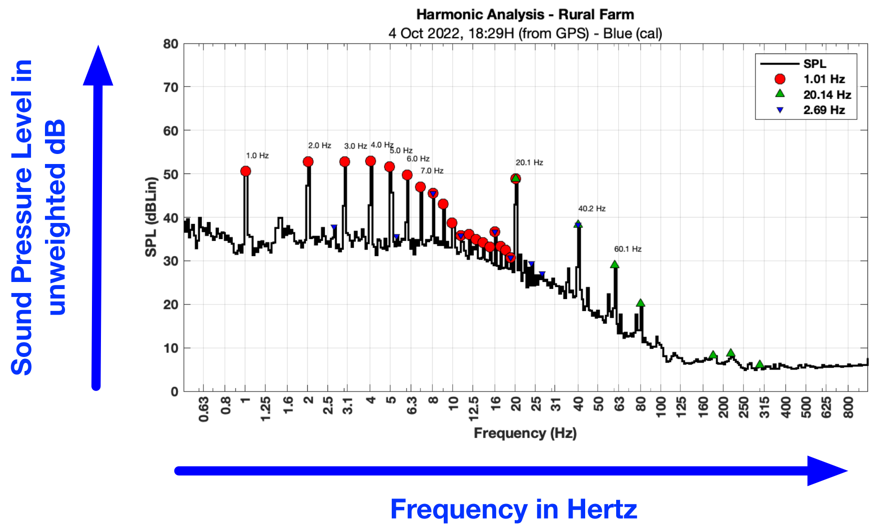


Figure 10. In this harmonic analysis from the same sound file as used for Figure 8, the sound pressure level (SPL) is averaged over each 600-second recording at each 1/36th-octave frequency. This SPL value, in dB-Linear or dB-unweighted (see **IX. Differences Between IARO Analyses and Legislated Methodologies**), is shown on the Y-axis and the corresponding frequency values (in Hertz) are shown on the X-axis. The upper right-hand corner lists the fundamental frequencies of the strongest harmonic series in descending order[11].

40. Figure 11 shows the correspondence between the Spectrogram data and the Sonogram data.

[11] For a full exploration of the MATLAB software that produces these Harmonic Series, please see "White Paper on the Harmonic Prominence Measure," IARO21-3 at https://iaro.org.nz/international-acoustics-research-organisationiaro/publications/white-paper/.

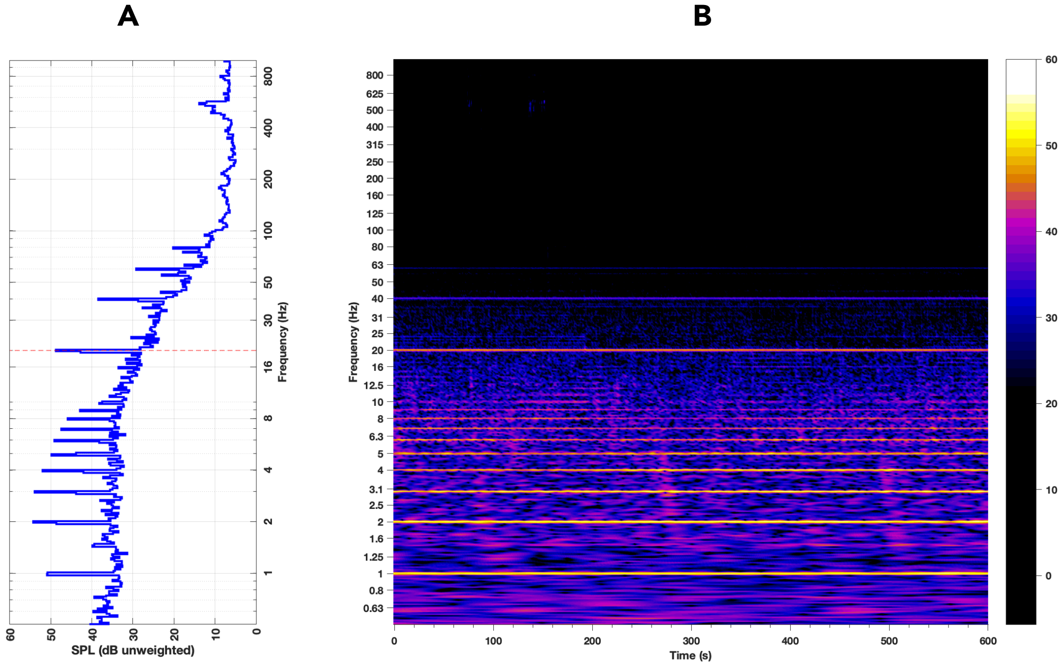


Figure 11. The relationship between the Spectrogram used for harmonic analysis (**A**) and the Sonogram (**B**). The frequency axis for both is vertical. For example, the red, dotted, horizontal line in **A** shows the audible /infrasound boundary at 20 Hz with a tall peak almost reaching 50 dB (blue horizontal line overlapping the red, dotted line). This is mirrored in **B** where the peak appears as a bright, horizontal line, also (of course) at 20 Hz. Numerical values for SPL (in unweighted dB) are obtained at each 1/36th octave frequency as an average over the entire 600-second recording. SPL values can be read on the horizontal axis in **A** and in the horizontal lines in **B**, using the colour-coded scale at the right of **B.**

41. Figure 12 points out the harmonic series with a fundamental frequency, F_0, of 1.0-hertz, already identified in the Sonogram shown in Figure 8.

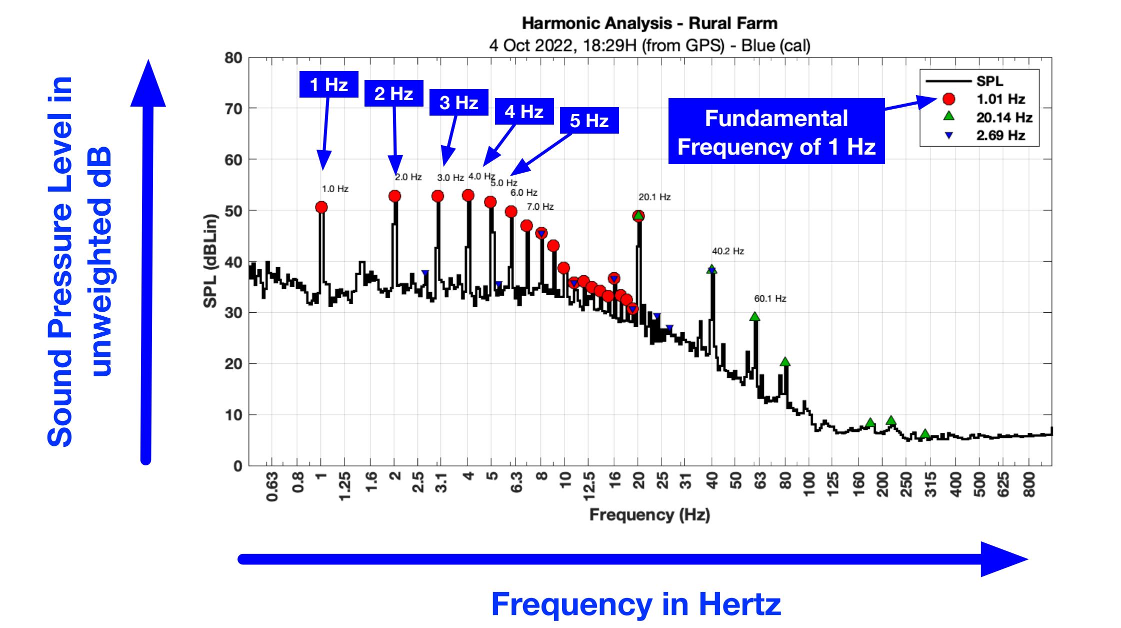
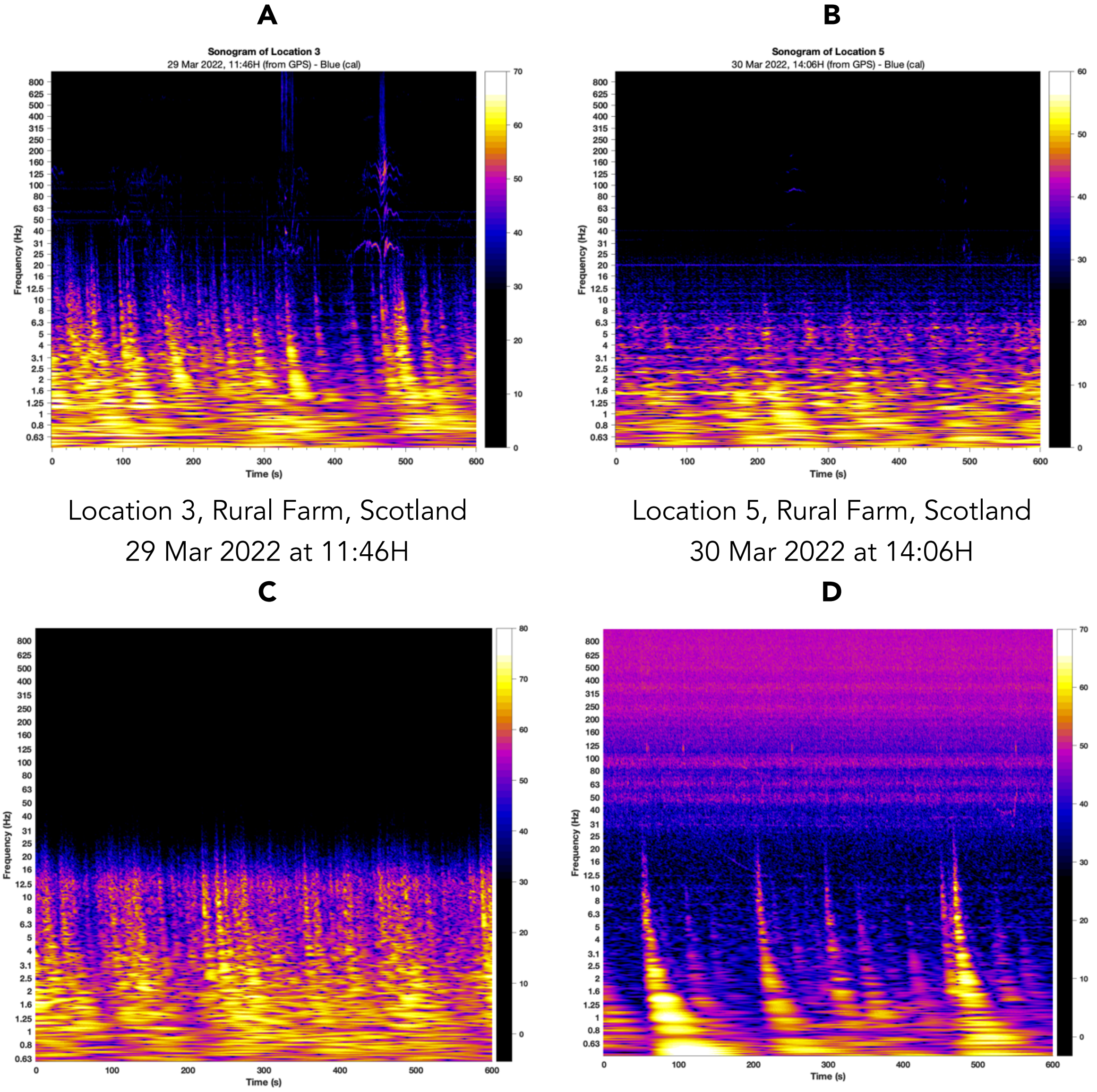


Figure 12. Spectrogram showing the SPL value per 1/36th-octave band, in unweighted dB and averaged over the 600 seconds. The regularly spaced peaks, beginning at 1 Hz (=F_0) collectively represent the 1-hertz harmonic series.

42. Harmonic series such as the one shown in Figure 12, reflect the acoustic output of a machine. Wind noise does not present as harmonic series.

43. Figure 13 shows four Sonograms recorded in different acoustic environments with several natural phenomena—wind gusts, beach waves and a river course—and where WTASs, if present, are barely visible.



Location 3, Rural Farm, Scotland
29 Mar 2022 at 11:46H

Location 5, Rural Farm, Scotland
30 Mar 2022 at 14:06H

Beach, Rømo Island, Denmark
13 Dec 2016 at 01:10H

Roaring Stream, Ballantrae, Scotland
24 Aug 2017 at 09:00H

Figure 13. Four Sonograms showing examples of wind gusts (**A** and **B**), wave noise (**C**) and stream noise (**D**). Wind gusts, waves and water noise are characterized by tall, triangular shapes that skew to the right at the base (in the infrasonic range). Note the loudness of the stream (**D**) in the audible (upper pink region, continuously at or above 50 dB) region of the sonogram as compared with the other examples where audible sounds are at much lower levels.

44. Nature does not tend to show itself in straight lines and well-defined harmonic series. These are features that can be traced back to the operation of machines or of human-made structures. A possible exception is an aeolian harmonic series caused by wind over a structure that either vibrates, or has trapped air that vibrates, as a result. A case of the former a (human-made) harp with tuned strings, an aeolian harp, where the wind causes the strings to vibrate, making notes or chords (see Fig. 14).

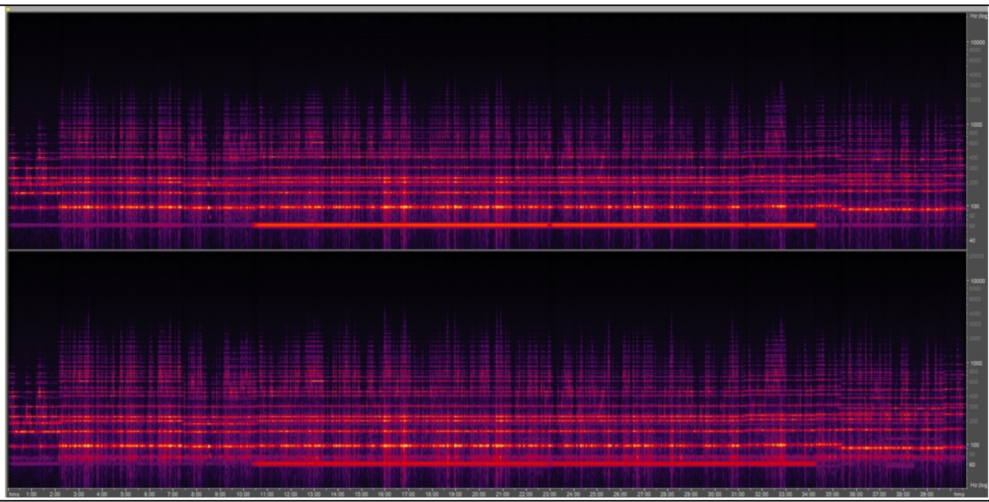


Figure 14. Sonogram of an electric, aeolian harp composition, recorded in stereo (upper and lower sonograms). The time axis is 40 minutes long; the log frequency axis spans the audible range.

The horizontal lines are tones caused by the flow of air over the strings, eliciting resonance. These form harmonic series, seen as horizontal lines with decreasing separation with increasing frequency (upwards). Several harmonic series can be seen at each point in time, corresponding to chords (multiple notes being played simultaneously. (Retrieved from https://chrisvaisvil.com/music-for-concentration-electric-aeolian-harp-harmonic-series/.)

45. Amplitude modulation is associated with the "whoosh" or "swishing" sounds that can emanate from a wind turbine (see Para. 15). Amplitude modulation is defined as:

> *"Periodic fluctuations in the level of audible noise from a wind turbine (or wind turbines), the frequency of the fluctuations being related to the blade passing frequency of the turbine rotor(s)." — Institute of Acoustics*[12]

46. Figure 15 shows the sonogram of a wind turbine with pronounced amplitude modulation co-existing with WTAS.

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12 Amplitude Modulation Working Group, (2016). "A Method for Rating Amplitude Modulation in Wind Turbine Noise," Institute of Acoustics, UK, 9 August 2016, p2. See Para. 83 for a definition of blade passing frequency.

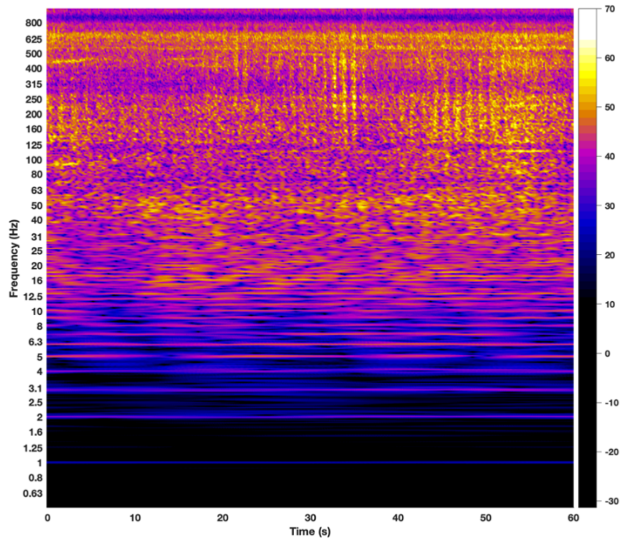

Figure 15. Sonogram of a 1-minute recording in the vicinity of the Makara WPP near Wellington in New Zealand (9 October 2009 at 02:39H, no wind data available). The phenomena of Amplitude Modulation as applied to wind turbines is shown as the bright yellow staccato-like pattern seen over a pink background, but only in the upper (audible) portion of the frequency spectrum. Notice that the corresponding WTAS is also present. Moreover, since Amplitude Modulation is a machine-generated acoustical phenomenon, it too appears at straight (vertical) lines.

47. In Figure 15, the brighter, vertical lines (in the upper, audible region) are the times when the sound becomes louder, leading to the "whoosh" sound that is often described. This occurs at one-second intervals (i.e., at a frequency of 1 Hz) as seen by the spacing between the vertical bars.

48. In the lower frequency and infrasonic region of the sonogram (see Fig. 15, lower half), horizontal lines are visible, indicating the probable presence of WTAS. These horizontal lines start at 1 Hz and repeat every hertz upwards, in other words, a 1-hertz harmonic series. Both the amplitude modulation and the WTAS have the same frequency, 1 Hz, because they are both produced by the blades at the blade-passing frequency (BPF) (see Para. 83).

49. Both the amplitude modulation phenomena and WTAS appear in the Sonogram as straight lines, indicating that these acoustic disturbances of the natural soundscape are human-made.

III. Harmonic Prominences

50. There are no stipulated methodologies for analysing harmonic series within the context of WTAS and human health.

51. IARO scientists have therefore been compelled to establish new variables, or parameters, in order to be able to better scrutinize these harmonic series particularly because:

52. <u>Premise 1</u>: Prior studies indicate that the presence of WTAS is correlated with adverse health effects such as inability to sleep[13].

53. <u>Premise 2</u>: With some exceptions, each fundamental frequency of a harmonic series identified within the infrasonic range corresponds to a IWT blade-pass frequency.

54. <u>Fact</u>: Harmonic series can be differentiated among each other by their fundamental frequencies.

55. Therefore, three variables were defined: *Harmonic Prominence*, *Harmonic Sound Pressure Level* and *Peak Harmonic Prominence* (P_{peak})[14].

56. Figure 16 visually represents these variables.

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13 "Infrasound exposure: High resolution measurements near wind power plants," (2023) In: *Management of Noise Pollution* (Online ISBN 978-1-83768-656-8). Book Chapter authored by IARO Scientists: https://www.intechopen.com/chapters/85225.

14 See "White Paper on the Harmonic Prominence Measure," IARO21-3 at https://iaro.org.nz/international-acoustics-research-organisationiaro/publications/white-papers/

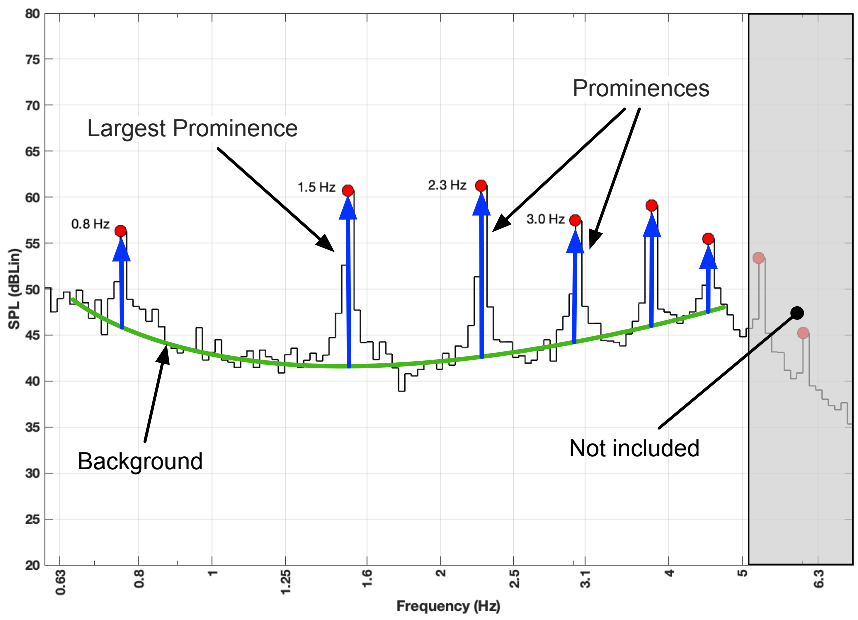

Figure 16. Visual representation of variables defined by IARO scientists to study harmonic series associated with WTAS. The green curve shows the acoustic background level against the peaks of the harmonic series that indicate the presence of a WTAS. (Data recorded in Casais do Monte, Portugal, 29Jul 2020, at 03:20H, Wsp = 2.2 m/s (7.9 km/h); Wdir = NNW).

Pressure pulses (WTAS) are emitted regularly from IWT turbine and appear as a series of peaks forming a harmonic series (red circles) when plotted against frequency. The prominence of these peaks above the background (green curve) sound pressure level (SPL) is the length of the blue arrows. The Peak Harmonic Prominence (P_{peak}) is the SPL value of the largest prominence in the series, as measured above background level, i.e. the length of the longest blue arrow. In this case, the fundamental frequency of the WTAS is 0.8 Hz. The peak harmonic prominence, P_{peak}, is defined as the highest peak above background level within the series. In this example, it occurs at 1.5 Hz with a SPL of approximately 18 dB.

57. **Peak Harmonic Prominence, P_{peak}, is the** SPL value (in unweighted dB) of the highest harmonic prominence in the series. (The more restrictive P_{harm} limits this to the peaks between 0.5 and 5 Hz, where WTAS peaks are found.[14])

IV. Fundamental Frequency Analysis

58. Given the above premises and scientific fact (see Para. 52–54), it becomes important to tally how many times each harmonic series, identified by different fundamental frequencies, is detectable throughout entire recording periods, and what is its peak value.

59. Using the SAM system, 1 hour of recording yields six 10-minute sound files for each microphone. Since recording periods can extend over several weeks, data acquisition can yield thousands of 10-minute sound files.

60. Figures 17-19 show examples of graphs (histograms) that are useful in identifying important harmonic series over a full recording period.

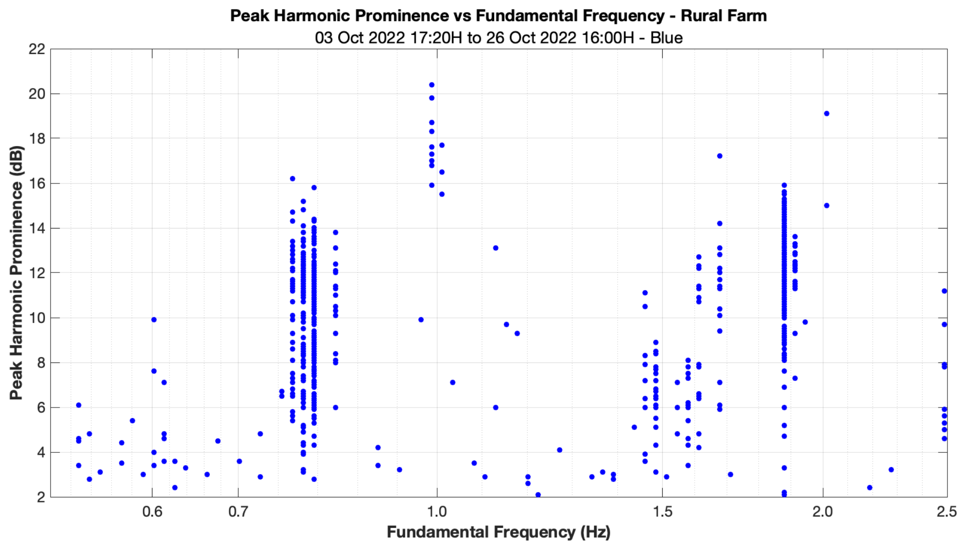

Figure 17. Graph of the largest Peak Harmonic Prominence (P_{peak}) in each 10-minute sound file against its Fundamental Frequency, over the 0.5 to 2.5 Hz range. This graph is based on data contained in 3157 10-minute sound files. (Data recorded at a rural farm, Scotland, 3–26 October, 2022.)

The largest P_{peak} (in unweighted dB, Y-axis), is plotted against the fundamental frequency of its harmonic series. When many Peak Harmonic Prominences are clustered around a given fundamental frequency—here, clusters are seen around 0.8 Hz and around 1.85-1.9 Hz—this indicates that the harmonic series with that specific fundamental frequency occurs often. Although the 0.8-hertz series and the 1.85-1.9-hertz series are the most frequently occurring in this sample, the highest P_{peak} was captured at 1 Hz, about 22 dB over background level. The highest P_{peak} of the 0.8-hertz cluster and the 1.85–1.9-hertz cluster were approximately 16 dB above background level.

61. Figure 18 shows the number of times each harmonic series (identified by their fundamental frequencies) was present in the 3175 samples of recorded sound files.

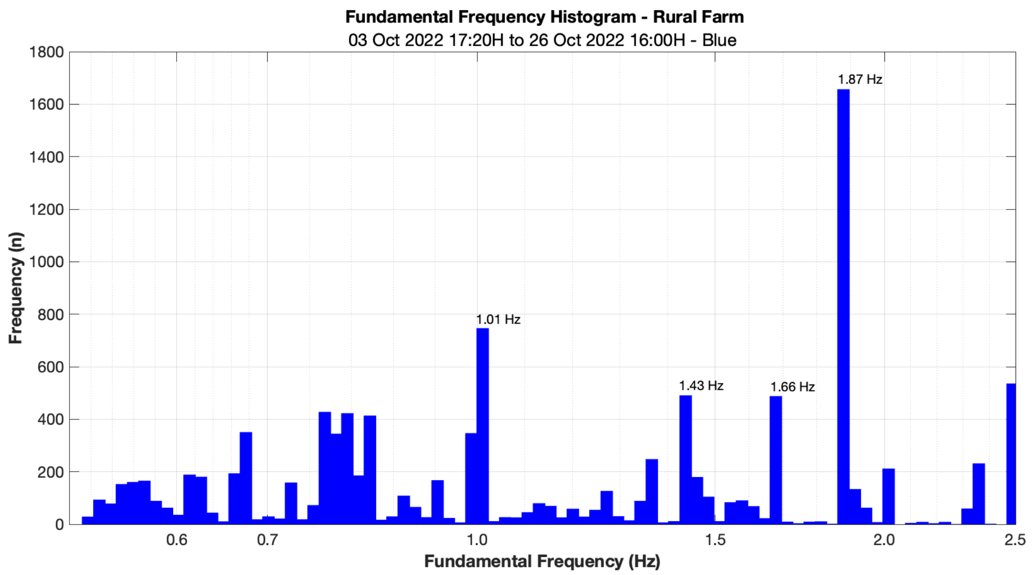

Figure 18. Histogram of the Number of Occurrences against the Fundamental Frequency, over the 0.5 to 2.5 Hz range. This histogram is based on data contained in 3157 10-minute sound files. (Data recorded at a rural farm, Scotland, 3–26 October, 2022.)

This histogram counts the number of 10-minute recordings in which a given harmonic series (identified by its fundamental frequency) is detected. (Note: This may have more occurrences than points in the Peak Harmonic Prominence graph (see Fig. 17) as it includes all harmonic series detected in a 10-minute sound file, not just the strongest.) Here, the most often seen harmonic series occurred with a fundamental frequency near 1.87 Hz (detected in over 1600 of the 3157 sound files). The second most common had a fundamental frequency of 1.0 Hz (detected in over 750 sound files). The more spread-out cluster in the 0.75-0.85 Hz range is significant because the total number of occurrences was above 1500.

62. In the above examples (Figs.17 and 18), the frequency range for analysis was 0.5-2.0 Hz. This range can be extended to 20 Hz, as shown in Figure 19, with a different set of data.

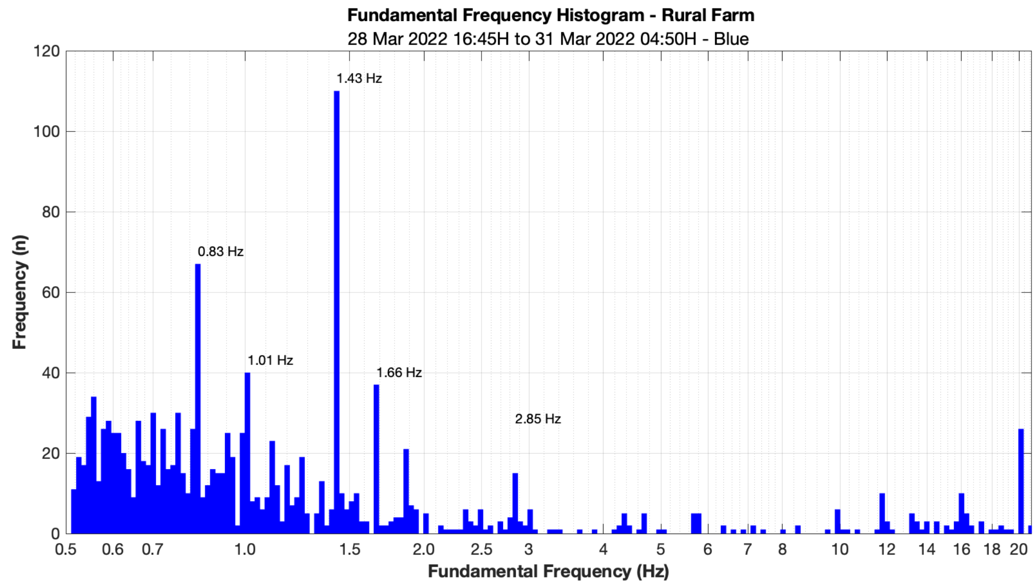

Figure 19. Histogram of the Number of Occurrences against the Fundamental Frequency, over the 0.5 to 20 Hz range. This histogram is based on data contained in 310 10-minute sound files. (Data recorded at a rural farm, Scotland, 28-31 March, 2022.)

In this recording sample, the most often seen harmonic series occurred with a fundamental frequency of 1.43 Hz (detected in over 100 of the 310 sound files) followed by the 0.83 Hz series (detected in over 60 sound files). This means that wind turbines rotating with a BPF of 1.43 Hz and wind turbines (of a different model) rotating with a BPF of 0.83 Hz are very frequently present in the vicinity of these recordings. The 20-hertz series with about 30 occurrences is not due to WTAS, as the fundamental frequency is far too high.

V. Time-of-Day Plots

63. WTAS are trains of short-duration pressure pulses that occur regularly every half to 2 seconds, depending on the wind turbine model. For proceeding with the investigation into potential health effects caused by WTAS exposures, it is necessary to ascertain how long each series exists over an extended period time[15].

64. With the Fundamental Frequency analyses, the most frequent series, and the SPL of the corresponding highest peaks (P_{peak}) were identified.

[15] In Medical Sciences, this is equivalent to ascertaining, or gaining insight, into the *exposure time* to infrasonic agents of disease. This is further discussed in a separate IARO Report, No. IARO24-C1.

65. Time-of-Day vs. Day plots were chosen to display the variation of P_{peak} (highest peak in each series above background level) over an extended period of time.

66. Figure 20 shows an example of a Time-of-Day vs. Day plot for P_{peak} corresponding to the harmonic series with fundamental frequency of 0.76 Hz.

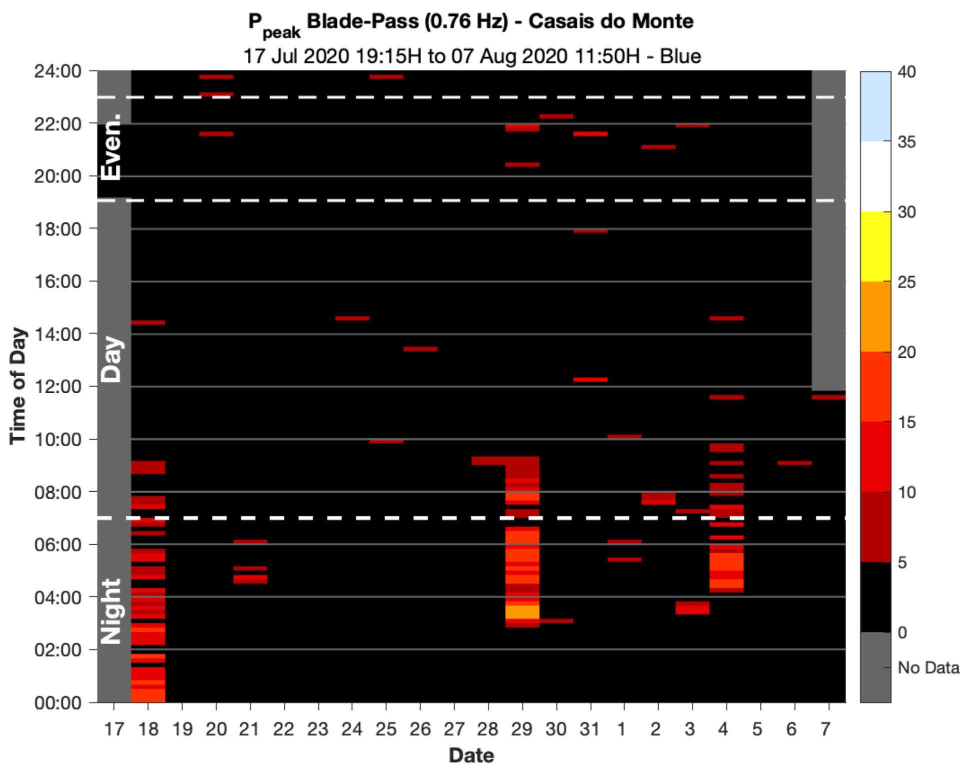

Figure 20. Time-of-Day vs. Day plot showing the variation of the level of P_{peak} (in unweighted dB) as a function of the time of day and day of the month. (Data captured in Casais do Monte, Portugal, Jul-Aug 2020, based on 2974 10-minute sound files)

67. Figures 21 and 22 provide aides to reading these types of graphs.

68. In the Time-of-Day plot, the vertical columns represent each day, while the horizontal slots represent the times of the day. There are 144 dashes in each column, or day, as there are that many 10-minute periods in one day. The colour scale on the right-hand side of the graph indicates the SPL of P_{peak} (see Fig. 21).

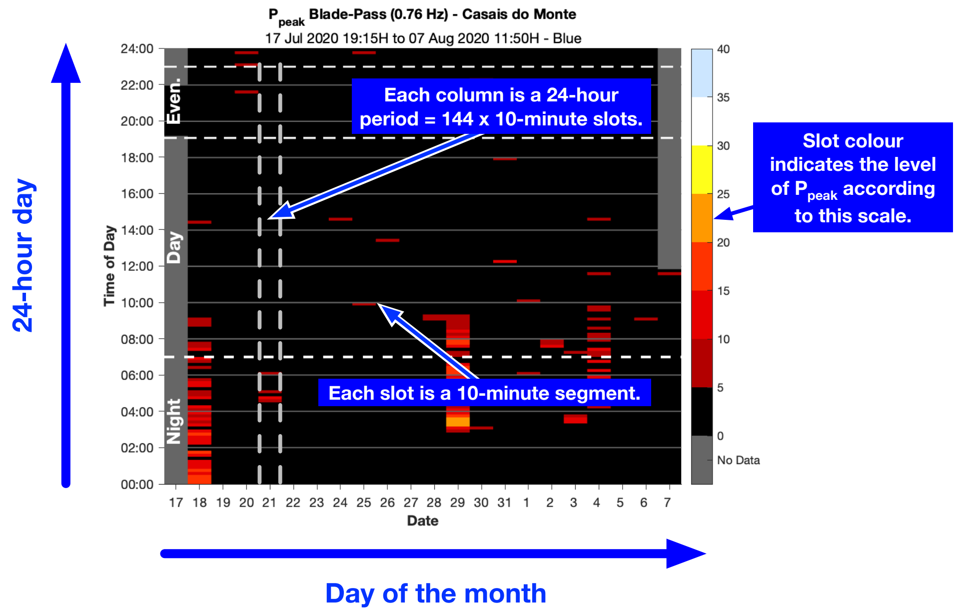

Figure 21. Time-of-Day vs. Day plot with labels indicating the most important features of this type of graph. Grey shows where no data is present, i.e., there were no sound files. Black shows 10-minute intervals where the P_{peak} was between 0 and 5 dB (over background level). In the Time-of-Day plot, the vertical columns represent each day, while the horizontal slots represent the times of the day in 10-minute segments. There are 144 slots in each column. The colour-coded scale provides the SPL value for P_{peak} in unweighted dB.

Figure 22 emphasizes the early morning of hours on the 29th (of July 2020). It was on this morning that the residents of this home felt compelled to take medication (benzodiazepines) in order to "cope with the noise"[16].

[16] "Infrasound exposure: High resolution measurements near wind power plants," (2023) In: *Management of Noise Pollution* (Online ISBN 978-1-83768-656-8). Book Chapter authored by IARO Scientists: https://www.intechopen.com/chapters/85225.

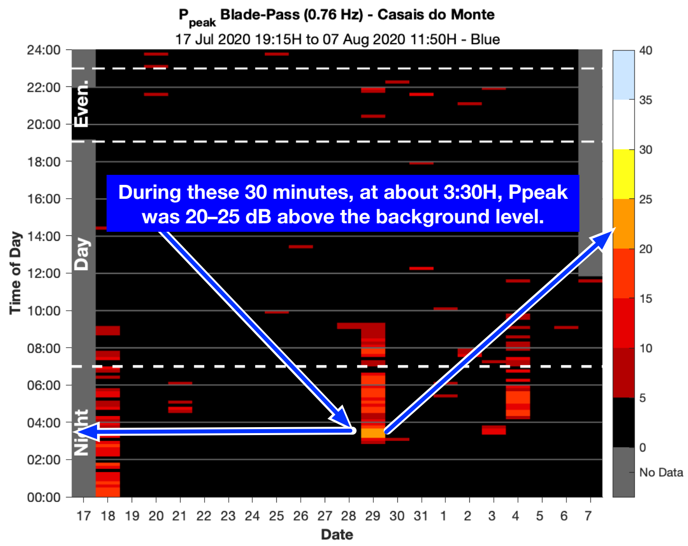

Figure 22. Time-of-Day vs. Day plot emphasizing the 30 minutes where P_{peak} was over 20 dB above background level. Diary entry showed that on this morning, residents felt compelled to self-medicate.

69. Sometimes, more than one WPP surrounds a given residence. In those cases, more than one WTAS might be detected, depending on the number of different wind turbine models.

70. Figure 23 compares a Time-of Day plot for all harmonic series within the 0.5—20 Hz range that were detected at a rural farm in Scotland, with that collected at Casais do Monte in Portugal.

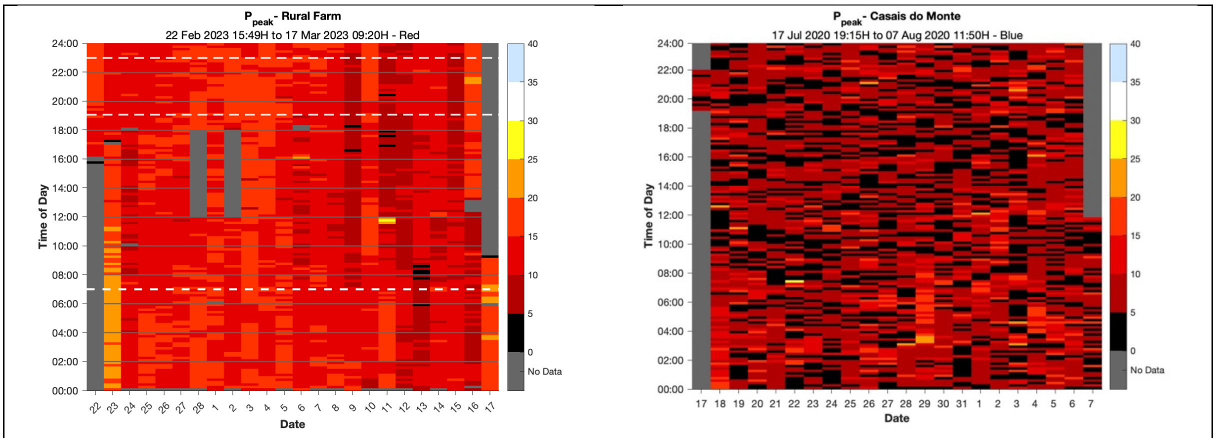

Figure 23. Time-of-Day vs. Day plot for the peak harmonic prominence (P_{peak}) over all harmonic series detected within the 0.5–20 Hz range. **A.** Rural Farm, Scotland (data recorded on 22 Feb–17 Mar 2023, based on 3175 10-minute sound files). **B.** Casais do Monte, Portugal (data recorded on 17 Jul–7 Aug 2020, based on 2974 10-minute sound files).

In **A**, P_{peak} is frequently seen at 10–15 dB and at 15–20 dB above background level (red and light red slots). The yellow dash on 11 March, at roughly noon, corresponds to a 20-minute period when P_{peak} was between 25–30 dB above background level. With the exception of the very infrequent and sporadic appearance of black slots, the saturation over time demonstrated by this plot means that REDACTED residents were continuously exposed to human-made/artificial low-frequency and infrasonic acoustic phenomena for, practically, 24 consecutive days.

In **B**, the number of black slots is significantly increased as compared to **A**. This means that the number of sound files that registered P_{peak} at below 5 dB is larger than that registered at the rural farm. It follows that the overall time over which exposures to P_{peak} were at or above 15 dB is significantly less than in **A**.

71. IARO scientists postulate that consecutive exposures over days at a time, such as those shown in Figure 23A, likely inhibit residents' ability to contribute with useful diary entries, given the difficulty of temporally pinpointing the onset or disappearance of a particular symptom. This was the case seen at the Rural Farm, where useful diary entries were not forthcoming, due to lack of precision.

VI. Wind Roses

72. Meteorological wind roses usually display wind speed as a frequency histogram wrapped around a circle. That is, each bar of the histogram indicates the number of intervals where the wind came from that direction, with each segment in the bar representing a different range of wind speeds.

73. Figure 24 shows a wind rose where P_{peak} is plotted instead of the wind speed. The length of each coloured section of a bar identifies the number of 10-minute recordings that had a P_{peak} value as indicated by the colour-coded scale. Simultaneously, it indicates the direction from which wind was coming during those 10-minute recordings.

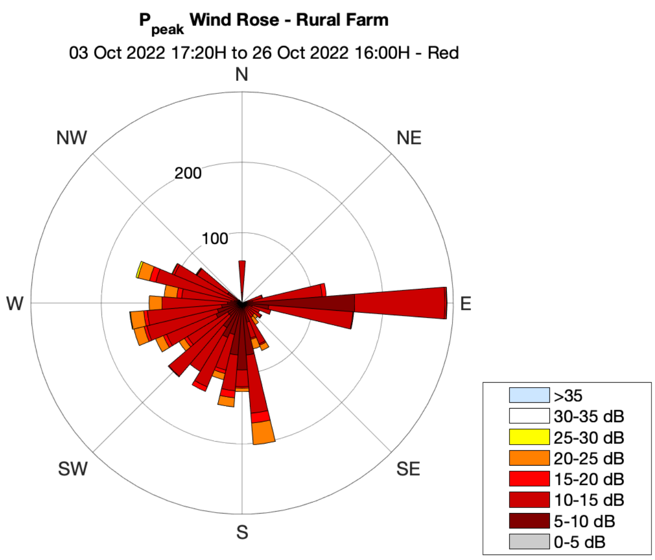

Figure 24. A P_{peak} wind rose recorded at a rural farm, Scotland (Recorded on 3–26 October 2022, based on 3157 10-minute sound files).

The direction of the bar identifies the wind direction, and the colour of the section identifies the SPL of the P_{peak}, in unweighted dB. Since the sections of each bar are stacked, the numbers on the inner circles indicate the cumulative number of 10-minute recordings.

74. Figure 25 offers a more detailed explanation of how to read P_{peak} wind roses.

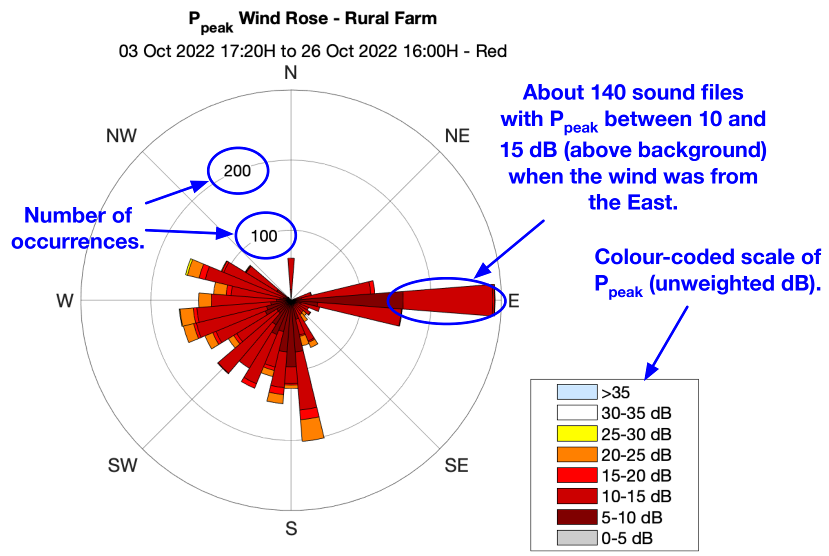

Figure 25. A P_{peak} wind rose for the October recording period at Rural Farm.

The relative lengths of the bar sections are the proportion of 10-minute recordings compared to the total number. In this wind rose the two longest bars are for wind from the east and wind slightly east of due south. The easterly bar shows a shorter grey section than the southerly bar indicating that the former has less time with P_{peak} in the range of 0–5 dB and more time in the 5–10 and 10–15 dB range.

75. Wind roses showing P_{peak} have become useful tools to assess if certain harmonic series are more frequent in one or another wind direction, or from which wind direction are they entirely absent.

VII. Waveform Analysis

76. The waveform is the shape of the signal that is measured by the microphone over time. A harmonic series is derived from a waveform that is repeated at a constant rate. This rate determines the pitch of the sound. The height of the waveform determines the sound level. It is the shape of the waveform that determines the character of a sound; through waveform analysis it can be determined whether a certain sound resembles a flute or a violin.

77. This type of analysis attempts to find the underlying waveform that is responsible for the harmonic series seen amongst the background noise.

78. Two types of analyses can be performed:

79. The first—the synthetic-waveform method—filters the recording at the frequencies of the harmonic peaks and then adds all these filtered signals together to create a synthetic waveform. An example is shown below in Figure 26.

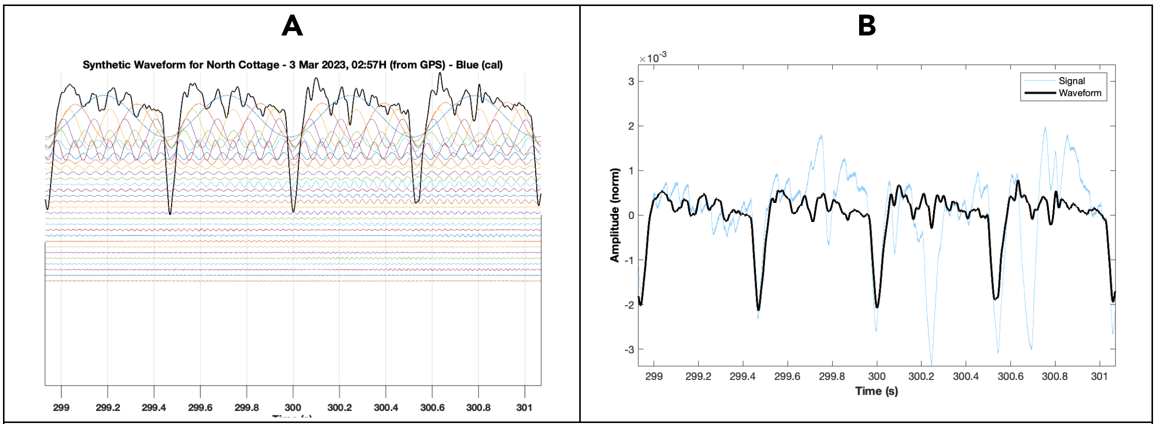

Figure 26. The 1.0-hertz waveform was reconstructed from the 10-minute segment captured at a rural farm, Scotland (3 March 2022, starting at 02:57H, Wsp = 3.6 m/s (13 km/h), Wdir = ENE). The synthesised waveform is shown here for the two seconds between 299 and 301 seconds from the start of the recording. The waveform is reconstructed by adding the waveforms of the signal after filtering at each of the harmonic frequencies. These can be seen in **A** with the signal from the lowest frequency at the top (blue) and from the highest frequency at the bottom (orange). The combined (synthesised) signal is overlaid (black). The same synthesised signal is shown in **B** (black) with the original signal (blue). Note the close alignment of the troughs. The troughs correspond to a sound pressure level of 74 dB.

80. The second—the averaged-waveform method—takes a template waveform and looks for this template at set intervals in the time series. It then averages all those instances where the difference between the signal and the template are considered small enough. An example is given in Figure 27.

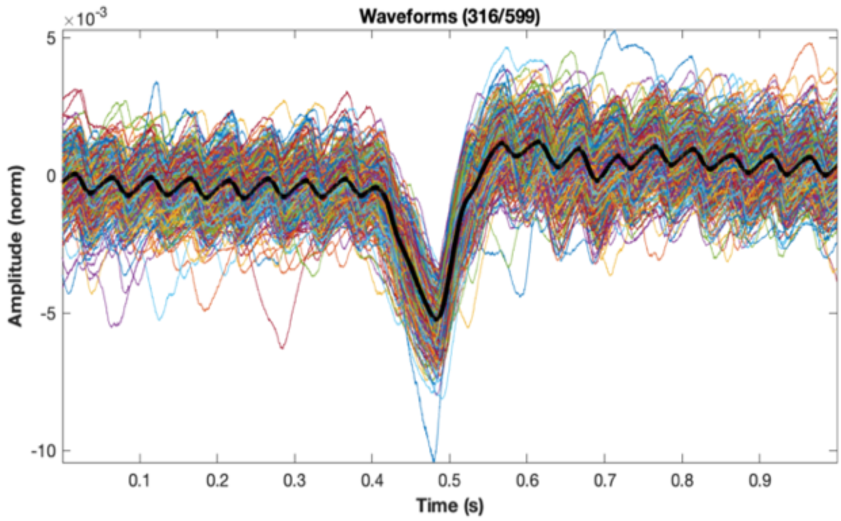

Figure 27. The 1.0-hertz waveform was reconstructed from the 10-minute segment captured at a rural farm, Scotland (3 March 2022, starting at 02:57H, Wsp = 3.6 m/s (13 km/h), Wdir = ENE). The averaged waveform includes over half (316 out of 599 = 52%) of the pulses in the recording, indicating that there is medium confidence that the waveform has been accurately captured. It also shows a train of pulses occurring at 1-second intervals and a 20-hertz ripple which appears to maintain the same phase with respect to the pulses. The troughs correspond to a sound pressure level of 74 dB.

81. When several IWTs are operating the waveform will have a more complex shape because it is the sum of all the individual waveforms. Experience has shown that, under the conditions of multiple IWTs, there is almost always one turbine whose WTAS predominates over the others.

VIII. Wind-Turbine Acoustic Signature, WTAS

82. Wind-turbine acoustic signature (WTAS) is a sound feature produced by all IWT at various noise levels and frequencies. It is seen as a series of pressure pulses over time that generally occur at a fixed rate, somewhere between about one pulse per every two seconds or (for more recent IWTs) two pulses per every second. The rate, or frequency of these pulses is determined by the BPF of the different IWT models.

83. The BPF (blade-pass frequency) of IWTs is defined as the frequency at which blades pass the tower of the turbine. A three-bladed turbine will have three blade-passes per full rotation. If such a turbine is rotating once every three seconds, 1/3 Hz, then its BPF will be three times this, that is, 1 Hz.

84. The pressure pulses caused by the aerodynamics of blade movements, will be detected at the same rate as the BPF. These pulses can either be positive (an increase in pressure), negative (a decrease in pressure) or a dipole (an increase followed by a decrease).

85. When multiple IWTs are operating, the pressure pulses from each become added together at any given point to produce a complex waveform with multiple peaks and troughs. Usually, one or more of the turbines produce larger pulses as can be seen in Figure 28. This is the distinctive feature of WTAS.

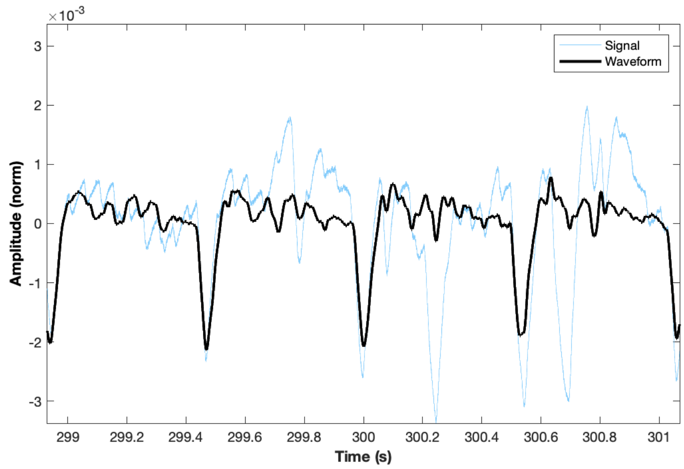

Figure 28. Wind turbine acoustic signature (WTAS) recorded in Rural Farm, Scotland (3 March 2022, starting at 02:57H, Wsp = 3.6 m/s (13 km/h), Wdir = ENE). This waveform has been reconstructed from the actual signal using the synthesised waveform method (see Para. 79).

86. The synthetic waveform in Figure 28 shows predominant dips in the time series that occur every 1 second, corresponding to the 1-hertz BPF of the IWT at the source of this acoustic signal.

87. In a spectrogram, WTAS is seen as a harmonic series with the fundamental frequency being the BPF. This can be seen in Figure 29 for the same sound file as in Figure 28.

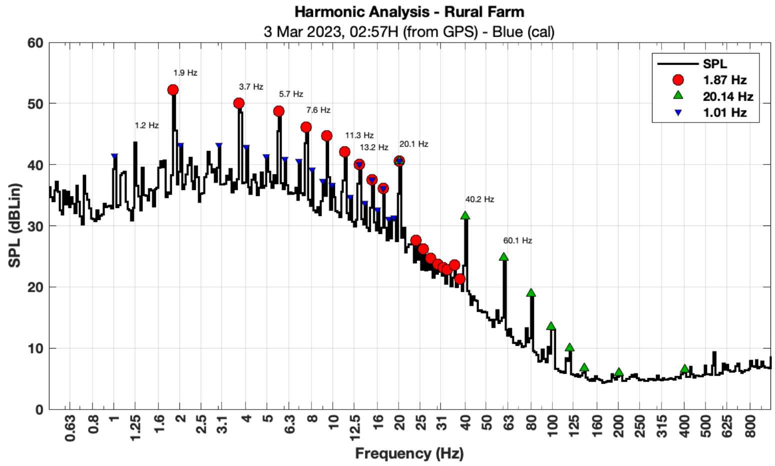

Figure 29. Harmonic analysis from a recording taken at a rural farm, Scotland (3 March 2022, starting at 02:57H, Wsp = 3.6 m/s (13 km/h), Wdir = ENE).
Two distinct WTAS can be identified: one with a fundamental frequency of 1.87-hertz (red circles) and another with a fundamental frequency of 1.01-hertz (blue triangles). Note that the 20.14-hertz harmonic series is not WTAS, since 20.14 Hz is far too high a value for a BPF, and no distinctive series of pulses exist when seen as a time signal.

88. Figure 29 showing two harmonic series—1.87-hertz and 1.01-hertz—suggests the presence of an IWT model that rotates with a 1.87-hertz BPF and, another, that rotates with a 1.0 Hz BPF. The 20-hertz harmonic series is not WTAS as there are no IWT with a BPF of 20 Hz. This does not mean that it is not associated with IWT as it might be the result of mechanical noise from the gearbox or other component of the IWT.

89. Sometimes, a harmonic series with WTAS characteristic is detected in the harmonic analysis, but no IWT with the corresponding BPF can be identified. It is possible that there may be two or three IWT with larger pulses, which may lead to a situation where there appear to be two or three pulses per blade pass.

90. When circumstances such as these are suspected, the data can be analysed for the existence of underlying harmonic series that maintain the WTAS characteristics, but whose fundamental frequency is one half or one third of the initially-detected series.

91. As an example, using the same data as in Figures 28 and 29, the 1.87-hertz series will be analysed to look for harmonic series with WTAS characteristics (distinct pressure pulses) and with a fundamental frequency of 1/2 and 1/3 of the 1.87-hertz fundamental frequency. This is shown in Figure 30.

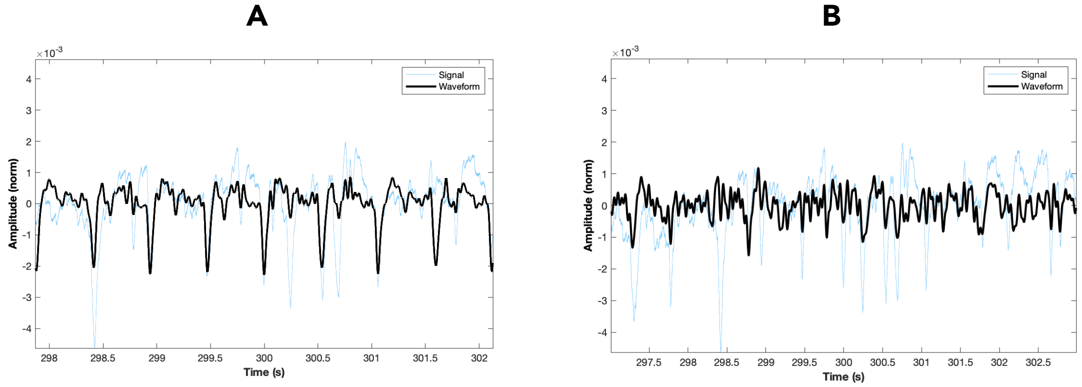

Figure 30. Reconstructed waveforms of a recording taken at a rural farm, Scotland (3 March 2022, starting at 02:57H, Wsp = 3.6 m/s (13 km/h), Wdir = ENE).

A. Reconstruction for a waveform with a 0.94-hertz fundamental frequency (i.e., one half of 1.87 Hz). **B.** Reconstruction for a waveform with a 0.67-hertz fundamental frequency (one third of 1.87 Hz). The WTAS characteristic is clearly visible in **A** as the equally-spaced peaks which are 0.53 (=1/1.87) seconds apart. This indicates the presence of IWT with a BPF of 0.94 Hz. No such WTAS characteristic is seen in **B** indicating that the 0.67-hertz fundamental frequency is not associated with a WTAS.

92. The reconstruction for a 0.94-hertz BPF (see Fig 30A) still shows the distinctive series of pressure pulses of WTAS, while that for a 0.67–hertz BPF (Fig.30B) does not. In the left graph the odd-numbered troughs (1^{st}, 3^{rd}, 5^{th}, etc) have slightly deeper troughs than the even-numbered ones. These would be from one wind turbine while the even-numbered troughs would be from another.

93. Looking at how the waveform varies over the length of the recording would show that the even-numbered and odd-numbered troughs change depth (slowly) independently of each other. This would be expected from wind gusts (for example) changing the depth of the pulses separately for each turbine.

94. This phenomenon will be referred to as 'twinning' since each blade-pass interval has more than one pressure pulse.

95. For further information, please see the two White Papers that IARO has created on analysis of harmonic prominence and harmonic sound pressure level[17,18].

[17] White Paper on the Harmonic Prominence Measure, IARO21-3, v6, 2021. Retrieved from https://iaro.org.nz/international-acoustics-research-organisationiaro/publications/white-papers/.

[18] White Paper on the Harmonic Series Metrics, IARO23-1, 2023. Retrieved from https://iaro.org.nz/international-acoustics-research-organisationiaro/publications/white-papers/.

IX. Difference between IARO Analyses and Legislated Methodologies

96. The sonograms and harmonic analysis described above allow for the identification of WTAS because of three factors:

a. increased time resolution,

b. increased frequency resolution, and

c. use of unweighted SPL.

97. Table 2 (reproduced from Paragraph 26 above) summarizes the major differences between IARO analyses and those required by Legislated documents and by Recommended Good Practice Guides (not just in the U.K.).

Table 2. Summary of Differences between IARO Analyses and other Analyses

Parameter	IARO	Other
Frequency resolution	1/36th of an octave	1/3rd of an octave
Time resolution	Second by second	10-minute averages*
Frequency-weighting	None (Unweighted)	A-, G- or C-weighting

* 1-minute and 10-second averages are also included in some situations.

98. Frequency resolution is increased from 1/3 of an octave to 1/36 of an octave. This is analogous to taking the length of a meter and breaking in into millimetre segments, in order to measure smaller things.

99. Time resolution is increased to a second-by-second recording. At each second in time, it is possible to know the SPL level at each 1/36 of an octave.

100. The SAM Technology uses microphones whose frequency response curve is given in Figure 2, showing a linear response within the 0.5—10 000 Hz range and thus yielding SPL values in dB-unweighted throughout this entire frequency range.

101. Figure 31 shows an example of a WTAS with a 1/36 octave resolution and a 600 second averaged SPL.

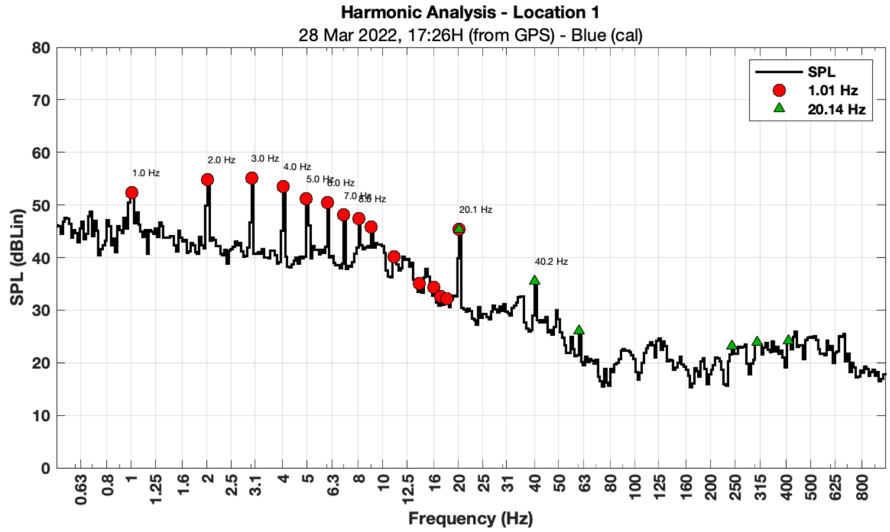

Figure 31. Ten-minute segment recorded at a rural farm, Scotland, starting at 17:26H (28 Mar 2022, Wsp = 1.9 m/s (7 km/h), Wdir = NW, microphone in Office).

IARO Analysis: in 1/36th octave bands, dB Unweighted. The presence of a strong WTAS is clearly identified—harmonic series with a fundamental frequency of 1 Hz.

a. A Frequency Weighting (dBA)

102. The A frequency-weighting filter is the most common weighting network, historically used world-wide to measure occupational and environmental noise. It yields numerical SPL values in dBA.

103. Figure 32 shows the frequency response curve for the A frequency-weighting filter.

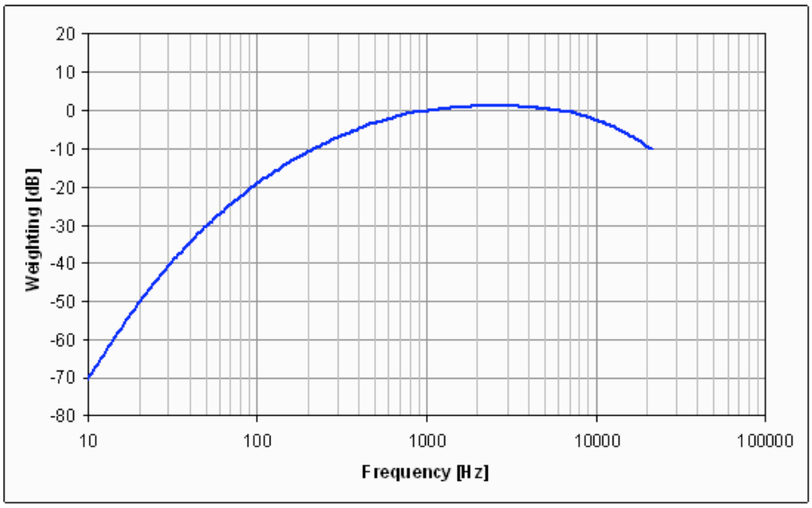

Figure 32. Frequency response curve for the A frequency-weighting filter[19]. Established in the 1920's, within the context of the developing telephone, the A-weighting filter simulates the peculiarities of human hearing.

104. The only airborne pressure waves considered of consequence for human health were those that could be *heard*, i.e., 'what you can't hear can't hurt you.' This belief justified the development of acoustic measuring devices and methodologies that concentrated solely on the audible portion of the acoustical spectrum (see Fig. 4).

105. Within the audible segment (20 to 20,000 Hz), human auditory acuity is not evenly distributed, and is more sensitive within the 800–7000 Hz range than it is to sounds occurring below 500 Hz or above 15 000 Hz.

106. Thus, early on, scientists understood that in order to protect human hearing function and speech intelligibility, the entire audible segment need not be considered, but rather, only the frequencies at which auditory acuity was highest: 800–7000 Hz range.

107. Subsequently, the development of the decibel-A (dBA) metric allowed acousticians and health professionals to assess acoustical environments simulating this variability in human hearing.

108. Figure 33 shows the A frequency-weighting response curve, emphasizing its appropriateness for protecting human hearing.

[19] ISO1996-2:2007(E). (2007). Acoustics. Description, measurement and assessment of environmental noise. Part 2: Determination of environmental noise levels. International Standards Organization, Geneva, Switzerland.

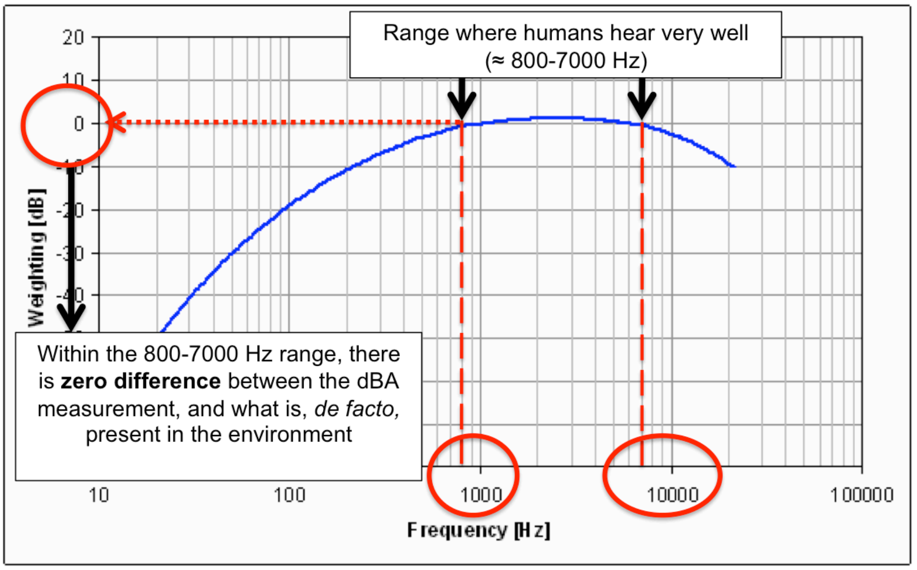

Figure 33. The A frequency-weighting filter was designed to protect human hearing which is most sensitive within the 800–7000 Hz range[20]. It is precisely within this frequency range that the A-weighting is zero, meaning there is no difference between what the SLM measures (in dBA) what is actually present in the environment.

109. As is graphically shown in Figure 33, the A-weighting was developed specifically to protect human hearing. Hence it is precisely within the range where human hearing is most sensitive that there is zero weighting, i.e., the SPL value (in dBA) measured with the SLM reflects physical reality.

110. As one decreases in frequency (below 800 Hz), there is an increasing discrepancy between what is being measured by the SLM (in dBA) and physical reality.

111. Figure 34 emphasizes the application of A-weighting at 10 Hz.

[20] Figure reproduced from "Acoustics and Biological Structures," (2019) In: *Acoustics of Materials* (Online ISBN 978-1-83880-350-6). Book Chapter authored by IARO Scientists: https://www.intechopen.com/chapters/64982

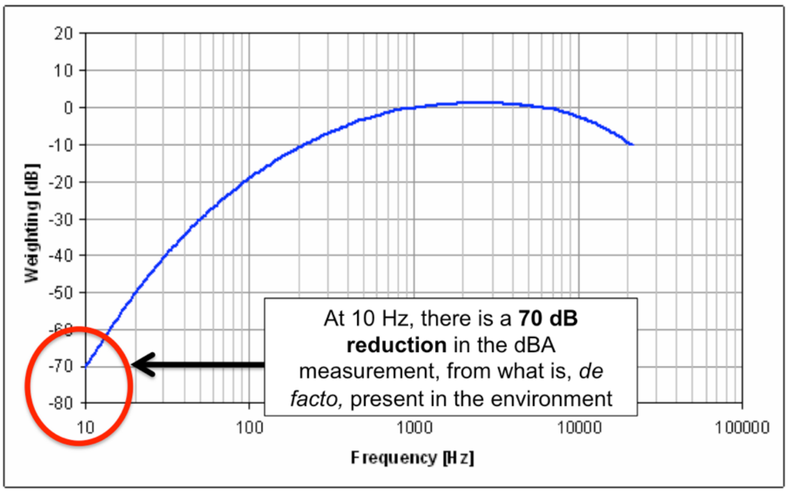

Figure 34. The frequency response curve for the A frequency-weighting filter applied to infrasonic frequency ranges[20]. Specifically, at 10 Hz there is a 70 dB difference between what the SLM measures (in dBA) and what is actually present in the environment. Within these lower-frequency and infrasonic ranges, SPL values provided in dBA will significantly underestimate the airborne acoustical energy present in the environment.

112. It Is clear that the dBA metric is patently unsuited for evaluating airborne pressure waves occurring at frequencies below 800 Hz. Health effects that may be developing due to exposures at these lower and infrasonic frequencies cannot be properly studied if the dBA metric is being used to characterize acoustical environments[21].

113. Figure 35 shows the 10-minute data set presented in Figure 31, but with the application of A-weighting (as required by most legislation worldwide).

[21] Redacted.

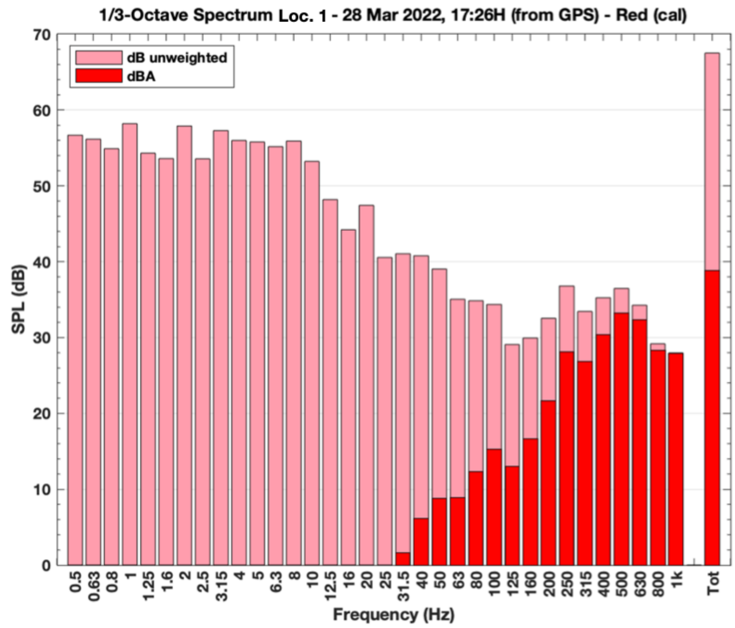

Figure 35. Ten-minute segment recorded at Rural Farm, Scotland, starting at 17:26H (28 Mar 2022, Wsp = 1.9 m/s (7 km/h), Wdir = NW, microphone in Office)—Same numerical data as in Figure 31.

Analysis as required by most legislation, in 1/3rd octave bands and with SPL given in dBA (red bars). The pink bars are in unweighted dB, not required by legislation but included here for comparative purposes. The red bars (i.e., that which is measured when the A-weighting is applied) represent only a small portion of the acoustic environment (merely the audible part) and all data below 20 Hz is truncated. The peaks at 1 Hz and 2 Hz (part of the 1-hertz harmonic series identified in Fig. 31) are fairly visible in the unweighted 1/3rd octave spectrum (pink bars) but are completely obliterated from the A-weighted analysis. The 20 Hz peak that is clearly present in Fig. 31, is also entirely absent from the A-weighted analysis.

114. The (large) amount of acoustic information that is lost with the use of the A frequency-weighting filter is represented by the pink bars.

115. Figure 36 shows the screens of the SAM system with and without the A-weighting applied[22].

22 SAM Technology allows for the on-screen, real-time visualization of microphone data acquisition, with or without the application of the A-filter. The recording of sound files in dB-unweighted is not altered, merely the setting of screen visualisation.

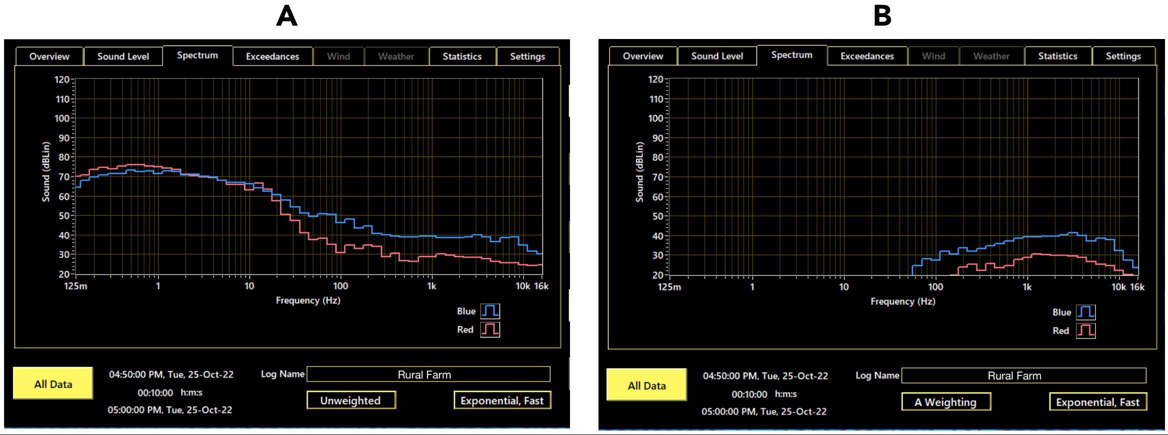

Figure 36. Recording at a rural farm, Scotland at 16:50 H (25 October 2022, Blue microphone was placed outside and the Red microphone in the Sitting room, Wsp = 7.2 m/s (26 km/h), Wdir = SSE). The blue curves reflect data acquisition with the Blue microphone and the red curve with the Red microphone. **A.** SAM tracing with unweighted dB setting on the screen visualization. **B.** SAM tracing with A-weighting applied to screen visualization. As can be clearly seen, when the A-weighting is imposed (**B**), the curves are truncated and do not reflect the physical reality as seen with the unweighted tracing (**A**).

b. C Frequency Weighting (dBC)

116. While the dBA metric proved to be key for the protection of hearing and speech intelligibility, particularly in occupational settings, it was insufficient for the assessment of airborne pressure waves occurring outside of the 800–7000 Hz range. The C frequency-weighting filter was subsequently developed, when airport, traffic and urban noise started to become an important issue for Public Health.

117. Figure 37 shows the C frequency-weighting response curve compared to the A frequency-weighting curve.

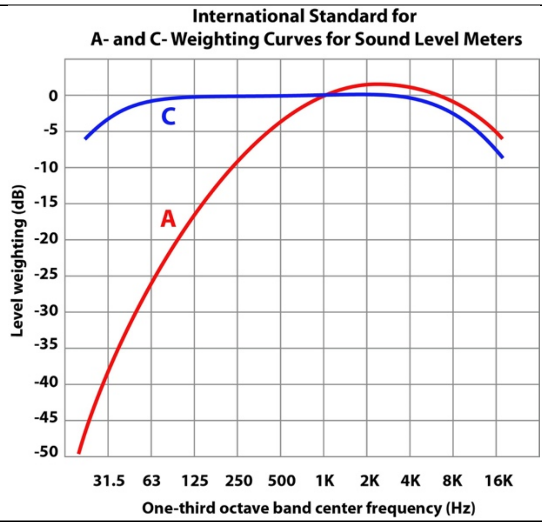

Figure 37. Frequency response curve for the C frequency-weighting filter and the A frequency-weighting filter[23]. Within 63–500-hertz frequency range, the C-weighting seems to better reproduce physical reality than A-weighting because, within this frequency range, the difference between what is measured with C-weighting and what is actually in the environment is zero (zero weighting). For frequencies below 63 Hz, the SPL is increasingly de-emphasized until, at 20 Hz, there is a 5 dB difference between what is actually in the environmental and what is read with a SLM when the C-filter is applied. The C-weighting (as the A-weighting) was not designed to capture acoustic events below 20 Hz.

118. Figure 38 shows the 10-minute data set presented in Figure 31, but with the application of the C-weighting.

[23] Image reproduced from HGC Engineering. Available at: https://acoustical-consultants.com/built-environment/noise-investigations/frequency-weighting-sound-level-measurements-a-weighting-dba-vs-c-weighting-dbc/attachment/dba-dbc/

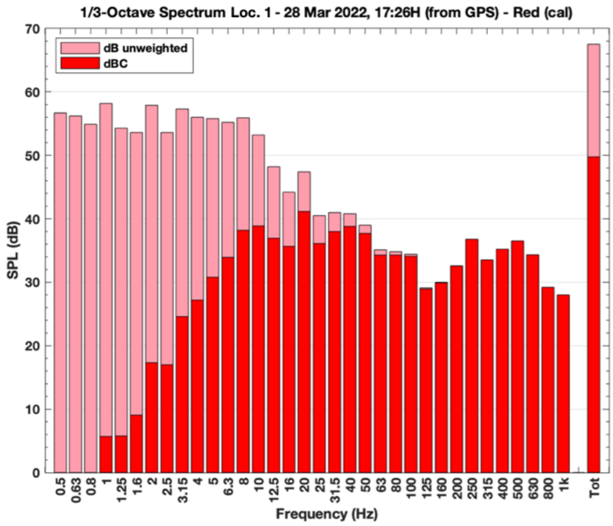

Figure 38. Ten-minute segment recorded at a rural farm, Scotland, starting at 17:26H (28 Mar 2022, Wsp = 1.9 m/s (7 km/h), Wdir = NW, microphone in Office). Same numerical data as in Figure 31.

Analysis in 1/3rd octave bands and with SPL given in dBC (red bars). The pink bars are in unweighted dB, not required by legislation but included here for comparative purposes. The red bars (i.e., that which is measured with the C-weighting) represent only a small portion of the acoustic environment, although clearly, not as small as when A-weighting is applied (see Fig. 35). Starting at 63 Hz and below, the difference between the pink and red bars increases considerably, reflecting the discrepancy between physical reality and what is being measured using a SLM with the C-weighting applied. The 20 Hz peak that is clearly present in Figure 31 and entirely absent from the A-weighting analysis (Fig. 35), appears to take on tonal characteristics—5 dB difference in both frequency bands adjacent to the 20 Hz band—when the C-weighting is applied. However, C-weighting analyses usually have a lower limiting frequency of 31.5 Hz and are not designed to go below 20 Hz. Therefore, the fact that there are tonal characteristics at 20 Hz goes entirely unnoticed[24].

[24] This is often justified by the belief "what you can't hear won't hurt you." Since 20 Hz is right at the threshold of human hearing, when a residential environment shows the presence of a continuous 20 Hz tone, it is generally assumed to have no impact on human health. This matter is discussed in more detail in IARO Report No. IARO24-C1.

c. G Frequency Weighting (dBG)

119. The last type of frequency-weighting filter discussed here is the G frequency-weighting filter[25]. This filter was, in part, developed due to the increasing number of noise complaints from citizens who point to low-frequency sound as the source of their unwellness. For IARO scientists, the rationale on which the use of the G-weighting is grounded has yet to be understood.

120. For the A- and C-weightings there was a range of frequencies where the weighting value was zero: 800–7000-hertz frequency range for the A-weighting (Fig. 35) and 63–4000-hertz frequency range for the C-weighting (Fig. 37). For the G- weighting, however, merely 2 individual data points see a zero weighting, at 10 Hz and 31.5 Hz.

121. Figure 39 shows the frequency response curve for the G Frequency-weighting filter.

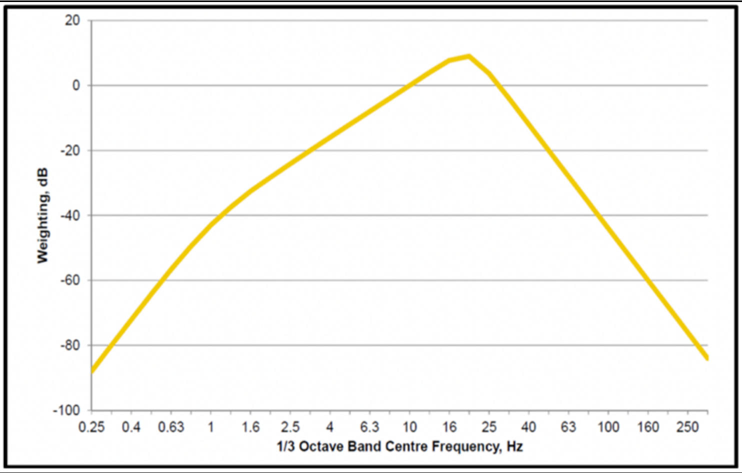

Figure 39. Frequency response curve for the G frequency-weighting filter[26]. Two data points see a zero weighting: 10 Hz and 31.5 Hz. In other words, a SLM with the G- weighting applied will only accurately measure physical reality at the two frequency points of 10 Hz and 31.5 Hz. In between these isolated data points (i.e., within the 10–31.5-hertz frequency range), the G- weighting overestimates the SPL value (meaning, the SLM will indicate a higher dBG level than what is, in reality, physically present). As the frequency value decreases from 10 Hz, the weighting values increase significantly—at 1 Hz, the discrepancy between physical reality and SLM-measured values is 50 dB.

25 ISO 7196:1995(E). (1995). Acoustics. Frequency-weighting characteristic for infrasound measurements. Geneva, Switzerland.

26 Image reproduced from "Systematic review of the human health effects of wind farms" (2014). University of Adelaide, Australia, National Health and Medical Research Council. https://www.researchgate.net/publication/265294499_Systematic_review_of_the_human_health_effects_of_wind_farms/figures?lo=1.

122. Figure 40 shows the 10-minute data set presented in Figure 31, but with the application of the G frequency-weighting filter.

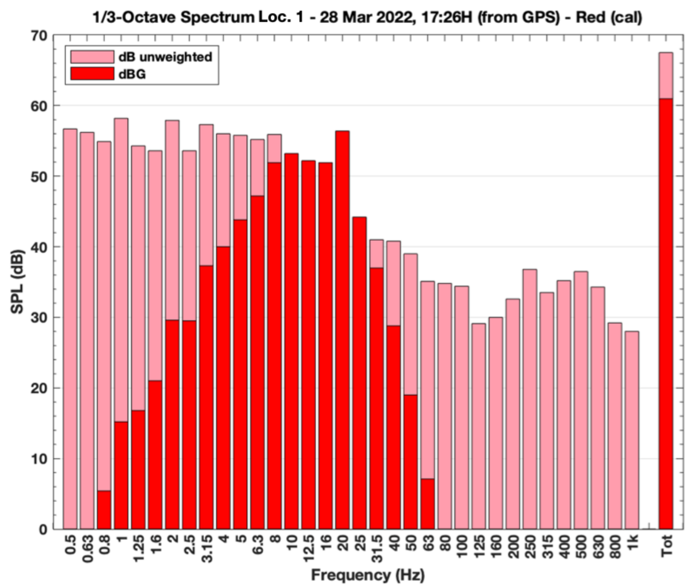

Figure 40. Ten-minute segment recorded at a rural Farm, Scotland, starting at 17:26H (28 Mar 2022, Wsp = 1.9 m/s (7 km/h), Wdir = NW, microphone in Office). Same numerical data as in Figure 31.

Analysis in 1/3rd octave bands and with SPL given in dBG (red bars). The pink bars are in unweighted dB, not required by legislation but included here for comparative purposes. The red bars (i.e., that which is measured with the G- weighting) represent only a small portion of the lower frequency and infrasonic environments. In Fig. 35 (or Fig. 38), the pink bars show that the 20-hertz tone appears with a SPL of less than 50 dB-unweighted. Using the G- weighting, the SPL level at 20 Hz appears as well over 50 dB, an over-estimation by approximately 10 dB. On the other hand, the 1- and 2-hertz peaks that are also visible in Figure 35 or Figure 38 (unweighted dB, pink bars) are entirely absent from the data collected with the G- weighting. Physical reality puts the SPL of the 1- and 2-hertz peaks at just below 60 dB, while the G- weighting value for the 1-hertz band is approximately 15 dB (one-fourth of the actual value) and for the 2-hertz band, approximately 30 dB (one-half of the actual value).

END