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A Citizen Science Initiative: Acoustical Characterisation of Human Environments

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ABSTRACT

The characterisation of acoustical environments where humans are present is generally performed by acoustics experts. Acoustical investigations generally return derived measures such as 10-minute (or longer), A-weighted measurements, and sometimes 10-minute, ⅓-octave bands and FFT Leqs, meaning that further analysis cannot be performed since the primary data, the actual sound, is no longer available. Obtaining full-spectrum data, including ILFN, for monitoring normally involves complex, non-standard instrumentation systems. Furthermore, the cost of such detailed investigations skews the frequency of investigations towards those environments where the owners can afford them.

As a component of a multi-disciplinary approach to such investigations a Citizen Science Initiative is presented to capture high-quality recordings from diverse environments where humans are present. Coupled with event identification/documentation, following an established protocol permits a cost/time effective process for assessments. A suitable recording system has been developed to support the initiative and a comprehensive protocol is available to ensure that recordings approach professional quality. A library of quality recordings will allow subsequent analysis and reanalysis by researchers in future.

INTRODUCTION

For much of the last century consideration of the acoustical environment in which we dwell has largely been synonymous with the audible-sound environment. While research has included consideration of infrasound and ultrasound, the day-to-day dealings of most acousticians appear to have been related to the measurement of audible sound as it relates to human perception, and to noise exposure limits. Indeed, the mantra that “what you can’t hear can’t hurt you” has in many ways defined the consideration of acoustical energy on the wellbeing of people in contact with it.

Much work has been done by the WHO [1-4] regarding what parameters should be considered when protecting human health and wellbeing against noise exposure. Of that, a subset has been used in the formation of many of the regulations [5-7 as examples] regarding safe levels of noise, in order to limit occupational hearing loss and to stipulate reasonable levels of noise for enjoyment of amenities (although what constitutes ‘reasonable’ depends heavily on location; the background noise level in downtown Copenhagen is much higher than that in some rural areas of New Zealand).

Throughout the definition, and refinement, of these regulations the emphasis has always been on the human perception of sound, so regulations are generally specified in terms of the A-weighted measure of sound level (although some, dealing with aircraft, for instance, use other measures). The use of the A-weighting filter uses the sensitivity of the human ear at 40 phon to weight the sound level at each frequency. It is therefore a measure of the sound level that people would hear, not a measure of the actual sound level (which would include the unfiltered energy at all frequencies). The implication in doing this is that the perception of sound is only via the ear and that human sensitivity follows the A-weighting curve at all sound levels.

Other assumptions are made regarding which characteristics of the acoustical environment are relevant for considerations of health and enjoyment of amenities; namely, that the average (LAeq) A-weighted sound level is, on its own, the most important parameter, with some additional consideration given to ‘special audible characteristics.’ The emergence of a noise above the background level, the A-weighted sound level—when averaged over an interval such as ten minutes (or even eight hours)—is the primary focus when dealing with noise levels associated with hearing loss and enjoyment of amenities. Special audible characteristics, such as hammering, an audible tone or short-duration jet noise, are then considered as adjustments above this level. That is, this second set of assumptions states that some consideration is given to special *audible* characteristics.

Absent from consideration is the possibility that there are other pathways by which acoustical energy may enter the human body and affect it. If such alternative pathways are allowed for when defining the safety and amenity of acoustical environments, then the current reliance on human hearing as the sole pathway of the human-sound interaction may well be totally unfounded. In fact, there are other pathways through which acoustical energy is perceived by humans [8], and more again where the human body reacts to acoustical energy without, necessarily being consciously perceived. For example in sleep studies, noises not accompanied by an awakening have been shown to cause biphasic heart-rate alterations where the initial acceleration was followed by a deceleration below the baseline and then by a slow increase back to the pre-stimulus levels [9].

Infrasound and Low-Frequency Noise

The investigation of infrasound on the human body over the last century has not been ignored [10]. Indeed, around the time of World War II, and for many years after, infrasound was considered to be a hot topic as a weapon that could incapacitate enemy soldiers [11-13]. These relied largely on sheer acoustical power at infrasound frequencies but also dealt with the apt choice of combinations of frequency that were most effective.

Beyond such effects from high-level infrasound, research has also shown that humans are far more perceptive of ‘inaudible’ sounds than the A-weighting filter would have us believe. For instance, the bass of any ‘decent’ stereo system, when heard some distance away, is perfectly capable of keeping someone awake at levels undetectable to A-weighted measurement above the background. The A-weighting is largely insensitive to these frequencies and a ten-minute average would not respond in any significant way to such a noise.

The work of Salt [14] has shown, for instance, that human’s perceptions of infrasound frequencies affect the inner ear without being heard, i.e. at levels well below the hearing threshold defined by the A-weighting standard. Other work [15] has shown that other organs within the human body can be affected by long-term exposure to infrasound frequencies.

The amount of infrasound and low-frequency sound generated by human industry has increased in the last century and, while the audible contamination of residential areas is guarded against by modern sound regulations, the contamination due to ILFN is largely unreported and unconsidered.

Measurement of Acoustical Environments

As a consequence of this too-narrow definition of the important aspects of an acoustical environment, measurements mandated by many regulations and standards may well be inadequate to measure the level at which human health may be impacted and at which the amenity of a location is degraded by the acoustical environment. We have already mentioned the severe limitations that the A-weighting filter and the 10-minute average have. And yet, these are the two most common measurements taken and reported.

In light of advances in instrumentation and further research into the full-spectrum of acoustical energies, we need to measure the entire acoustical environment to see what damage we may be doing to people.

When we measure these environments we need to capture the entire spectrum of acoustical energies. We must also be able to capture the physiological reaction of people to the acoustical environment, for which we need to capture their reactions and add this to telemetry of their physiological state. For instance, our research group has access to small heart monitors that can be attached to people to measure various parameters including respiration rate, heart rate, heart-rate variability and ‘R to R’ from beat to beat [16].

REQUIREMENTS

Data capture and instrumentation

To capture acoustical parameters normally required for legal purposes (such as compliance), requires sound level meters that have been typed as Class 1 or Class 2 and have valid calibration certificates from a suitable testing laboratory. However, these types of instruments are not well suited to fully capture an acoustical environment and are too expensive for use in a citizen science initiative.

Science is not just about hypothesis testing. Before a hypothesis is formed there must come observations upon which to make a hypothesis. In that situation we, as researchers, are not fully aware of what constitutes important data and we cannot say with any degree of certainty what the specifications should be for a recording to capture the characteristics of an acoustical environment. We might have the impression that ultrasound is not an issue to humans, although it might be. Further, we will have the impression that ILFN components are an issue and we would want to make sure that these are captured on a recording. Without knowing what the lower frequency threshold it would behove us to go as low as is practical.

It is common knowledge that the characteristics of an acoustical environment are time varying. There are many different parameters that affect such an environment, including weather (temperature, wind speed and direction, humidity, lapse rate, etc.), background noise, type of noise source (industrial, commercial, residential), as well as noise-source parameters (operation mode, load, production rate, etc.). Most of these will vary with time in ways that may, or may not, be predictable or measurable. Even if they were, we would not be aware, beforehand, which would be important. We would need to record the acoustical environment over long periods of time, for which we would need instrumentation that can record for possibly months at a time.

An acoustical environment will not be homogeneous over any significant area. Outdoors the environment may be reasonably homogeneous over tens of metres (apart from the interference effects from multiple sound sources creating ‘heightened noise zones’ possibly only a few metres across [17]). However, indoor environments can vary significantly over distances less than a metre. A measure of redundancy is needed to provide some safety against a rogue recording due to placement of a microphone. This means that multiple sound channels are needed to capture an acoustical environment and that multiple recording instruments may be required.

As a researcher, we would be attempting to characterise acoustical environments because we know that some characteristics of these environments have the potential to harm humans within them. We are not sure what these characteristics are. We do not know what sections of our months-long recordings are important. We do not know, generally, what many of the parameters surrounding noise sources are; production rates, loads, etc. are usually regarded as commercially sensitive and are not available. We do, however, have the ‘mine canaries’; namely, the humans themselves who are the indicators of when the acoustical environment is benign or malignant. If these people were to keep simultaneous diaries of their reactions to the acoustical environment we would have some indication of the characteristics of a benign or malignant acoustical environment. Of course, this assumes that the benignity or malignancy is directly related to a person’s reaction to the environment; this may not actually be the case.

There is the problem that ‘mine canaries’ are not objective instruments, nor are their reactions linearly related to the environmental characteristics, as we would wish. Ideally we would wish to have more objective measures, such as heart-rate monitors or blood pressure monitors, which are relatively free of subjectivity or subjective influence. Still, it is the subjective observations of the people that can usually be counted to identify periods of particular interest.

We come to the following summary of requirements for data capture and instrumentation:

1. Sound recording at high fidelity rather than immediate analysis.
2. Frequency range 1–20,000 Hz and optionally 0.1–1000 Hz.
3. Multiple channels of recording.
4. Continuous recording with data storage up to several months.
5. Common sound file format.
6. Optional capture of weather data.
7. Optional capture of physiological data.
8. Capture of metadata such as microphone location, recording parameters, noise source operation etc.

Citizen science

This being a citizen science initiative, a professional acoustician or scientist is not performing the capture of data. The average citizen has not had training in how to perform capture of recordings in the field, nor do they have a fundamental knowledge of sound that would allow them to deal with unforeseen issues. To this must be added the fact that citizens dealing with acoustics issues are often suffering from long-term sleep deprivation and therefore will have some degree of cognitive impairment.

This means that the instrumentation and software that is used to capture the acoustic recordings, and the procedures needed to set up equipment, must be simple, uncluttered and accompanied by a step-by-step set of instructions and checklists. The procedures must also not be too onerous to perform or the citizens will either not perform them correctly or will drop out of the initiative.

The other factor of great importance is the cost burden on the citizens participating in the initiative. They are volunteers who will receive no remuneration for their efforts and have limited resources. While several citizens can band together to purchase needed equipment, the cost of industry-standard equipment is usually beyond US$6000 per channel of sound. To be reasonably affordable this must be reduced to roughly US$1000 per sound channel.

It should be noted that, while citizens will not be remunerated for their efforts, they are not, in general, driven by altruism. Their reason for helping is often that they are impacted by noise and see that the initiative will provide an understanding of the issues they face, with the expectation that their situation will eventually be relieved.

This raises the issue of expectation management; citizens must be aware that any changes to their own situation may not occur or may be many years into the future. Indeed, if analysis of the acoustical environment in which they live provides no evidence that the environment is causing health issues, then they must be willing to accept this outcome.

The final factor is one of the outcomes of the initiative. What is it that the citizens will receive for their efforts? With the potential numbers of citizens, and the amount of data that they can capture (tens or hundreds of terabytes per month in total) it would be unreasonable for each and every recording from each and every citizen to be analysed by an expert. While such could be done for select recordings and citizens, it would need to be on a professional, charged-for basis. If the citizens were not solvent enough for this to be possible, they would not receive any direct benefit from the initiative.

A reference library of acoustical environments

There is a third path, however. It is possible for automated software to perform simple analysis on—but not interpretation of—the sound files. For instance, sonograms, spectrograms, and time plots can be readily created. If there is an automated procedure for uploading sound files, and a mechanism for citizens to retrieve the automated outputs, then this could be done with minimal cost.

As more data is created, uploaded, stored and analysed, it becomes possible to filter the data for exemplars of particular types of acoustical environments. In this way a library of such environments can be created. These can become the basis for further research (one of the obvious purposes of the citizen science initiative) but also can be used as a reference for citizens to compare their situation with others.

With further research it should be possible to add to analysis tools that can look for particular features of these exemplars. For instance, some recordings show evidence of a fundamental frequency with harmonics. Algorithms are available to identify these, as well as measures to determine their significance relative to the background.

One can ask what use providing sonograms and spectrograms would be to citizens who have, very likely, no knowledge of these things. The fact is that many of the citizens will be highly motivated to understand more about the acoustical environment in which they live and particularly about what aspects of it may be the cause of their distress. With tutorial information and exemplars readily available, many of the citizens will learn to understand sonograms and spectrograms and be able to recognise significant features of their own acoustical environments.

With this rudimentary training, they can act as a first filter on new data, noting when significant events are found in recordings and bringing this to the attention of the library custodians and researchers.

We come to the following summary of requirements for a citizen science initiative:

1. All equipment and software must be simple (probably minimally functional) and uncluttered.
2. The cost of involvement must be kept to a reasonable level, in the region of US$1000 per sound channel.
3. A step-by-step procedure must be created to walk the citizen through the planning, setup, operation and post-capture tasks.
4. Automated systems are needed to upload, store, and analyse sound files, and to return derived analysis outputs such as sonograms and spectrograms.
5. A reference library of exemplars of acoustical environments is needed to capture the distinguishing features of the environments.
6. Educational material is needed to provide citizens with help in learning how to interpret the analysis outputs, including exemplars of given acoustical environments.

THE CSI-ACHE

The CSI-ACHE consists of three separate parts; a sound recording system, a recording protocol, and a server containing the ACHE library and analysis software.

Sound recording system

A sound recording system was developed for this initiative as a proprietary system that uses; two microphones, a twin-channel, wide-spectrum sound card, a Windows notebook, a GPS unit and security hasp [18,19]. The system can accept USB hard disks for extended recording of up to several months. The sound card has no significant roll-off until about 0.1 Hz but includes a 1 Hz high-pass filter when 'micro-baroms' are present at such levels that they cause clipping.

Sound files are stored in the Microsoft WAV uncompressed format that includes metadata. The unit's location and the GPS-derived time are stored in the format's metadata fields. A digital signature is encrypted by the security hasp and also stored in the metadata fields. This provides chain-of-evidence for the files.

Recording protocol

The defining document for the CSI-ACHE is too long to include here, although the Table of Contents is included as Appendix 1.

In addition to the expected protocol for placement of microphones, calibration and procedures while recording, the protocol also deals with working with the SAM Scribe hardware and software, maintaining a diary, vetting files for privacy issues, triaging files, data transmission and interpretation of derived data.

Library and analysis software

The ACHE sound library resides on a Cloud-based storage service. Citizens will be given access to sub-directories into which they will be able to upload their sound files for analysis. They will also upload metadata, consisting of data-logging sheets, photos, and diaries. Calibration files (sound files with recorded calibration tones) are included for both the start and termination of the recordings.

The analysis software has been developed in Matlab [20], which has support for narrow-band filters to ANSI® S1.11-2004 standard, class 0. Figures 1 to 5 show examples of analysis outputs from the software.

Figure 1 shows a sonogram and spectrogram created by the analysis software, which runs in Matlab. These are created, not with FFTs, but using 1/36th-octave narrow-band filters. This maintains the logarithmic relationship that acousticians are used to and allows for better representation of details over several orders of magnitude. The frequency resolution can also be higher than that possible from FFTs at lower frequencies.

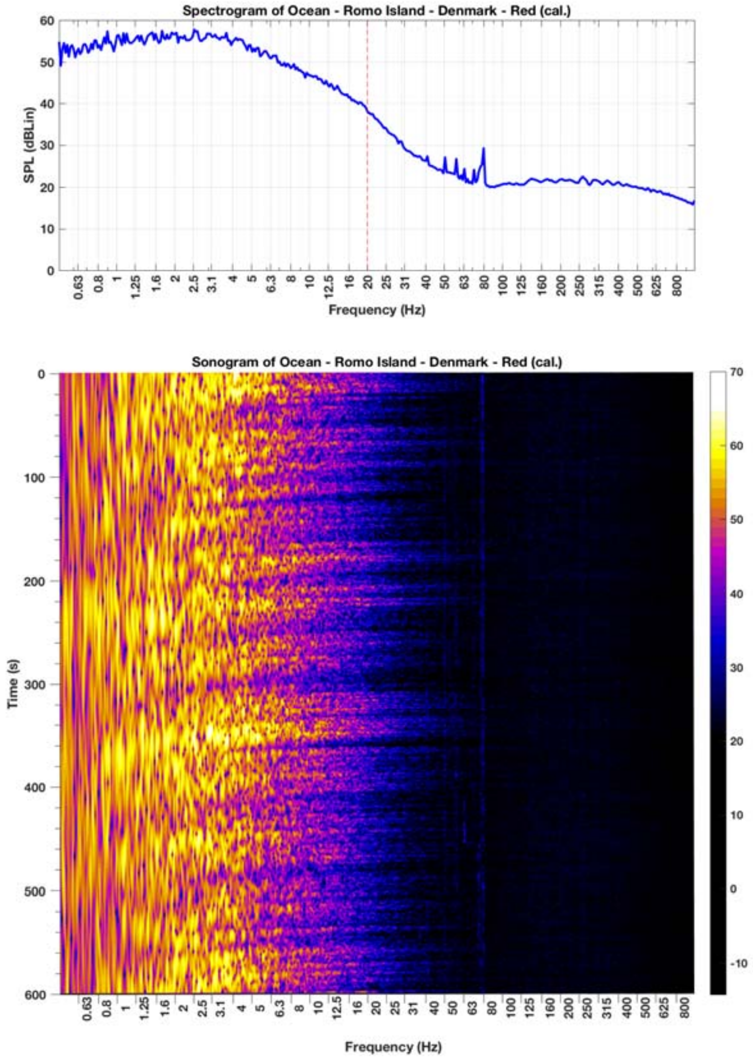

Figure 1: Sonogram and spectrogram from a recording at Romo Island in Denmark.

The graphs in Figure 1 are of the ocean at Romo Island in Denmark. Most of the acoustic energy is in the infrasound as one might expect. The horizontal striping on the sonogram indicates the noise of successive waves.

Figure 2 shows the sonogram and spectrogram from a diesel generator 1.5 km from the microphone. The strong vertical lines are mostly harmonics from a fundamental tone at 13.2 Hz.

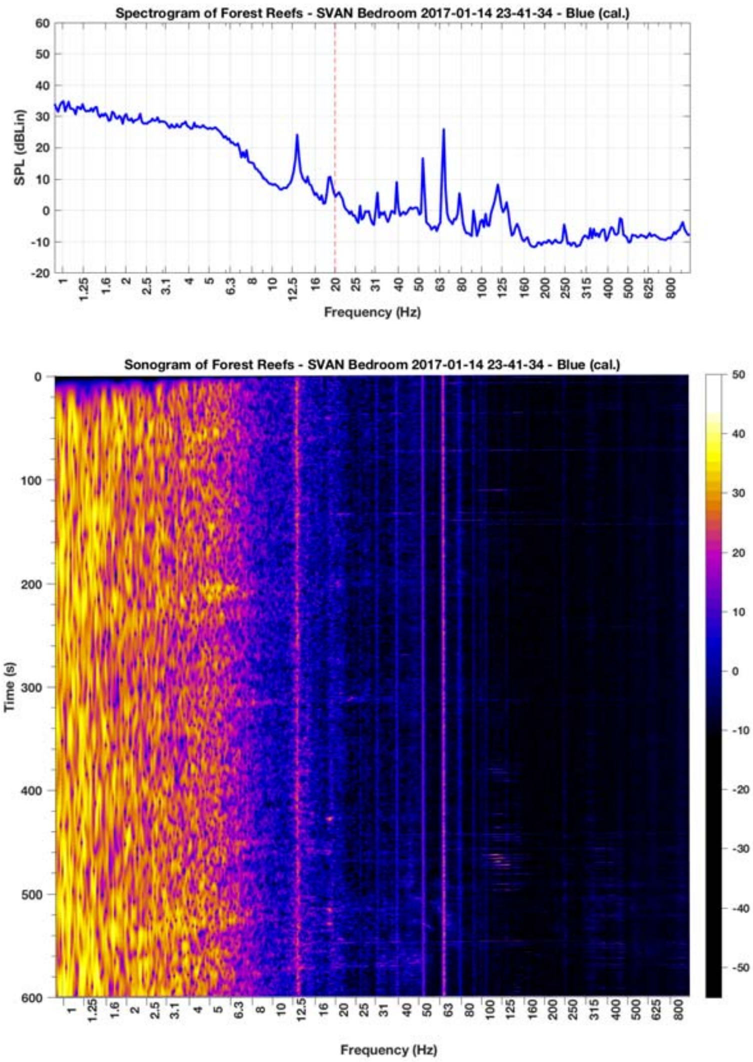

Figure 2: Sonogram and spectrogram of ILFN from a diesel generator. Note the horizontal lines at 350s, 125Hz from dogs barking.

The following Figures 3-5 relate to a wind farm in Makara, New Zealand. The first shows the sonogram and spectrogram where the 'swish-swish' can be seen in vertical lines from 1 Hz upwards (1 Hz is the blade-pass frequency) and in the horizontal striping at higher frequencies. The harmonics are all caused by the blade-pass-frequency fundamental as can be seen in Figure 4. Figure 5 shows a modulation plot of the same sound file where a low-frequency signal is heterodyned on the high-frequency carrier as amplitude modulation. The presence of energy in these various frequencies does not mean that these low frequencies are strictly present but only show up because of the pulsed nature of the high frequency components.

Together, these examples give some indication of the complexity of some acoustical environments and the analysis that can be automatically produced by the CSI-ACHE software.

Current status

At the time of preparing this paper, all three parts of the initiative have been developed and tested in prototype form.

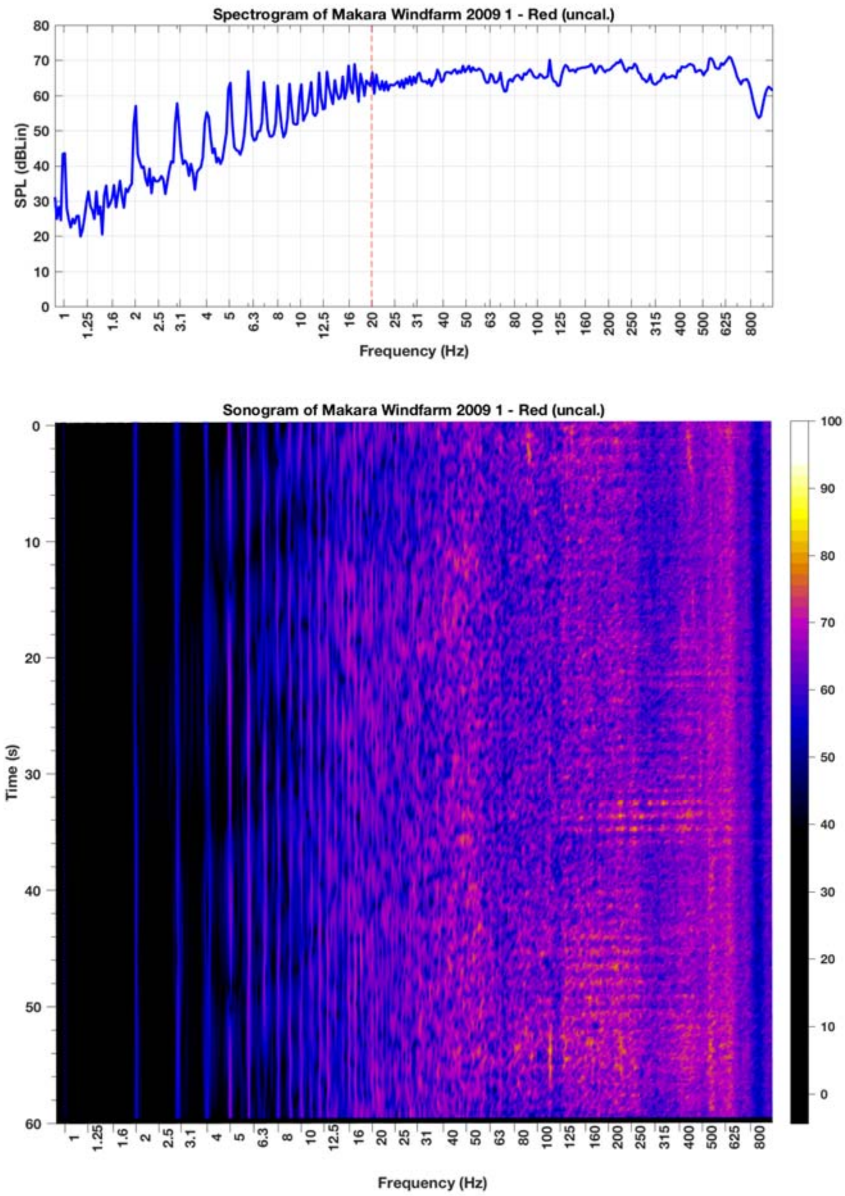

Figure 3: Sonogram and spectrogram of ILFN from a wind farm.

CONCLUSIONS

A better understanding is required of the characteristics of acoustical environments in which people spend time to identify the causes of noise-induced health effects, particularly in the ILFN region.

Continuous monitoring may be needed over months to capture important events that exemplify these characteristics. Alternative sound recording instruments are needed to provide this level of coverage at affordable cost.

A citizen science initiative is considered to be an apt vehicle to provide suitable data.

Such an initiative is presented here that includes: sound recording instrumentation, a full recording protocol, a library for storage of recordings and automated analysis of these recordings.

It is expected that the citizens themselves will provide filtering of the recordings and the automated analysis so that researchers will only be notified of significant events.

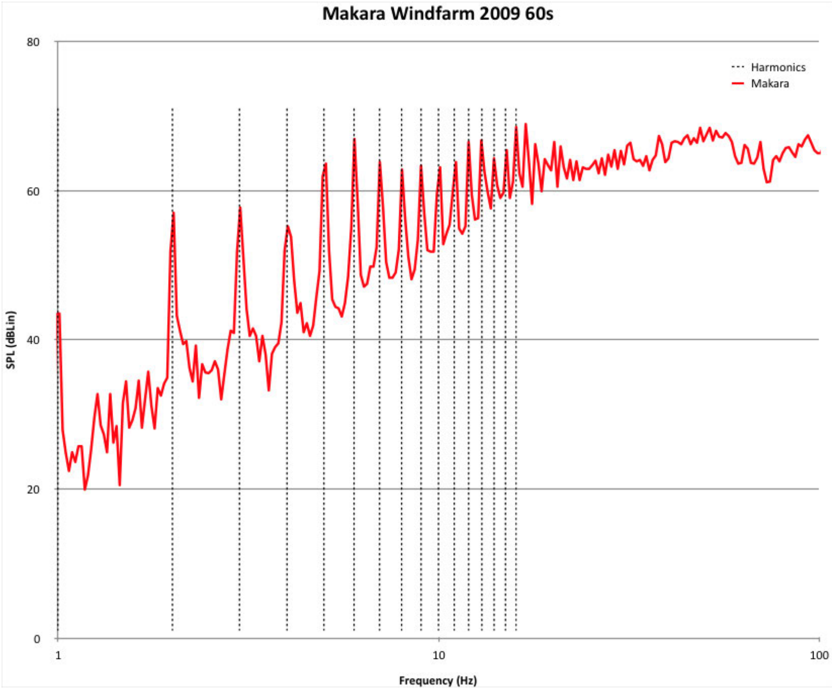

Figure 4: Spectrogram of ILFN from a wind farm showing the fundamental at the blade-pass frequency of 1 Hz and the first 15 harmonics.

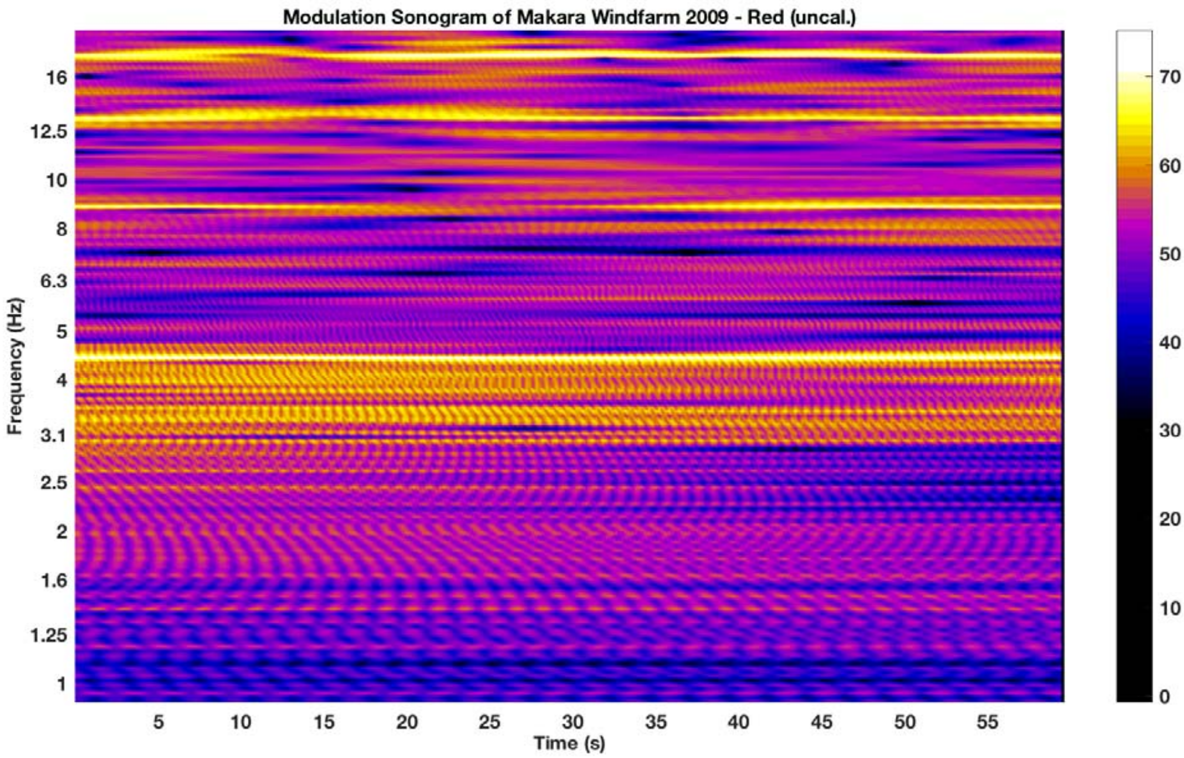

Figure 5: Modulation sonogram of ILFN from a wind farm produced by finding the amplitude envelope of the higher frequencies using a Hilbert Transform and creating a sonogram of the result.

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APPENDIX 1

The defining document for the CSI-ACHE is the ACHE Charter and Protocol. The Table of Contents is given below.