Novel Infrasound Monitor Project - real geophysics research on a budget

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Abstract. Described here is a well established opensource geophysics project to monitor atmospheric infrasound 24/7. It employs a modern digital, I^{2}C enabled differential pressure sensor - unlike the older analog devices more commonly used. Python software automatically uploads plots whilst data is stored in standard *.mseed* format for further analysis. Very open-ended with lots of opportunities for students of all levels, schools and above, to redesign and test replacement components. This is real science, in a little studied area. The equipment required is relatively cheap and offers many opportunities for students to build and refine a sensing system of research quality. It may be of interest as a national school's network producing results of real scientific and educational value at little cost.

1. Introduction

Infrasound is commonly defined as periodic air pressure variations at a frequency below the range of human hearing i.e. below about 20Hz. Signals with a period greater than 100 seconds (10^{-2}) Hz are swamped by variations due to the weather so typically the range of interest is $\sim$ 0.01 to 20Hz.

The human ear is sensitive to frequencies from $\sim$20Hz to $\sim$ 22kHz at birth. The upper frequency tends to decline with age and exposure to loud sounds. Amongst other mammals some cetacea such as porpoises may be sensitive up to 150kHz. Low frequency sensitivity has been less well studied however elephants are believed to communicate via infrasound and birds, such as homing pigeons appear to navigate using naturally occurring infrasound sources.

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Infrasound may be generated by natural and man-made events. Natural sources include volcanoes, earthquakes, avalanches, tides, lighting - especially in the upper atmosphere and meteors. Man-made sources may be air-conditioning, wind-farms, aeroplanes, rockets, large industrial plant, and explosions. An international network of infrasound monitors is used by the Comprehensive Nuclear-Test-Ban Treaty Organization (C.T.B.T.O.) looking for signals indicating an atmospheric nuclear explosion [1, 2].

Figure 1: CTBTO Infrasound 'Pipe Array' - Greenland [3]

Infrasound propagates well through the atmosphere and may be detected hundreds of km from the source.

2. Why Investigate Infrasound?

This is a fascinating relatively little studied area of geophysics wide open to further study. There was little research in the field before the 1960s. An infrasound monitor may be used as a static station, after storms, sonic booms etc. one may download the raw data files and analyse the signal. As a portable device it permits field studies near such sites of interest as wind turbines, quarries, airfields, and beaches.The system described here allows students to build a monitor capable of recording pressure variations of 4 x 10^{-2} Pa in the range 20 to 10^{-2}Hz.

2.1. Some Physics

Sound is a longitudinal periodic pressure variation of a fluid, the general physics of which may be readily found elsewhere.

However of particular note here is the frequency dependant attenuation of sound in air.

Stoke's law of sound attenuation gives the sound attenuation factor α for a *plane* wave as

$$\alpha = \frac{2\eta\omega^2}{3\rho c^3} \tag{1}$$

Where α is the attenuation rate (m^{-1}), η the dynamic viscosity coefficient (Pascal seconds), ω the wave's angular frequency ($rads^{-1}$) where $\omega = 2\pi f$, ρ the density of air and c the wavespeed.

It follows that the amplitude A at distance r is given by

$$A_r = A_0 e^{-\alpha r} \tag{2}$$

Acoustic I=intensity (Wm^{-2}) is defined as

$$I = \frac{A^2}{2\rho c} \tag{3}$$

where A is the amplitude (Pa), ρ the equilibrium density of air, and c the wavespeed.

We can therefore see that the amplitude attenuation varies as f^2 and thus the intensity varies as the square of this. This is one reason why infrasound may propagate over hundreds of km whilst higher frequency sounds attenuate much more quickly.

As the human ear is sensitive to a very wide range of intensities the loudness level is often expressed in decibels - the log of the ratio of the sound to some reference value.

$$L = 10log_{10}\frac{p^2}{p_{ref}^2} = 20log_{10}\frac{p}{p_{ref}} \tag{4}$$

Here p is the root-mean-square peak pressure and p_{ref} is typically 20μPa, approximately the minimum threshold of human hearing. It follows that a sound level of 120dB - such as at a loud rock concert, represents a peak pressure variation 10^6 times the threshold of human hearing.

3. Infrasound Detection

Infrasound may be monitored with either a ‘slow’ microphone or a fast pressure (barometric) sensor. Capacitive microphones have been used widely and whilst quite practical to build in a school workshop would add an extra level of build complexity and require very stable voltage supplies. Cheaper electret microphones suffer from a marked non-linearity at low frequencies [4] and the most widely tested low-cost one, the Matsushita WM-54D5, is no longer available.

‘Fast’ pressure sensors may be used , either absolute sensors which measure total atmospheric pressure or differential sensors measuring the difference in pressure between their two ports. For a resolution of say 0.1Pa an absolute sensor will need a resolution of 1:10^6, difficult to achieve requiring a very stable voltage supply as well as an ADC of some 20 bits resolution.

This system described here uses a digital differential device, employing a mems sensor to monitor the pressure difference between its two ports with a resolution of approximately 0.04Pa across a range of ± 125Pa. One port is connected to the atmosphere via some wind-shield whilst the other ‘reference’ port is connected to a slightly leaky enclosure - the backing volume. The sensor costs approx £40 and may be powered directly from the output pins of a Raspberry PI with which it also communicates via the 2 wire digital I^2C protocol.

Putting these in some context, a Chinook helicopter at 200m caused a peak pressure variation of $\approx \pm 0.25Pa$ whilst the 2020 Storm Denis generated $\Delta P \approx \pm 50Pa$ in north England.

4. The System

The system’s sensor is the Amphenol DLVR-F50D, a micro-electromechanical system (mems) where both electronic and mechanical components are fabricated on silicon. This particular device is a piezo-resistive differential pressure sensor with inbuilt temperature compensation. It internally converts the varying analog voltage across a silicon membrane into a digital signal which is transmitted over a 2 wire output using the I^2C protocol. The sensor’s range of ± 125Pa is divided into 6,553 steps giving a resolution of < 0.04 Pa. It is very simple to use with only 4 connections required. Gnd and +3.3V inputs are taken directly from the Raspberry Pi’s header pins whilst the two I^2C outputs (SDA & SCL) lead back to the Pi’s.

The authors have released open-source python software to read the I^2C signal, process, plot and store data.

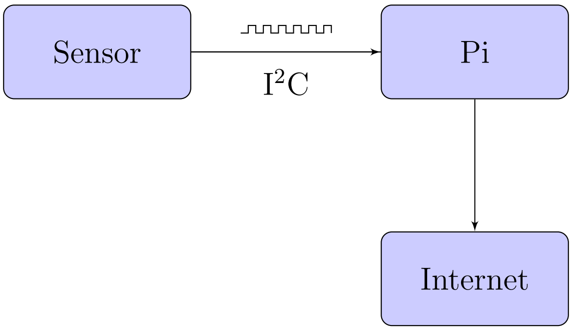
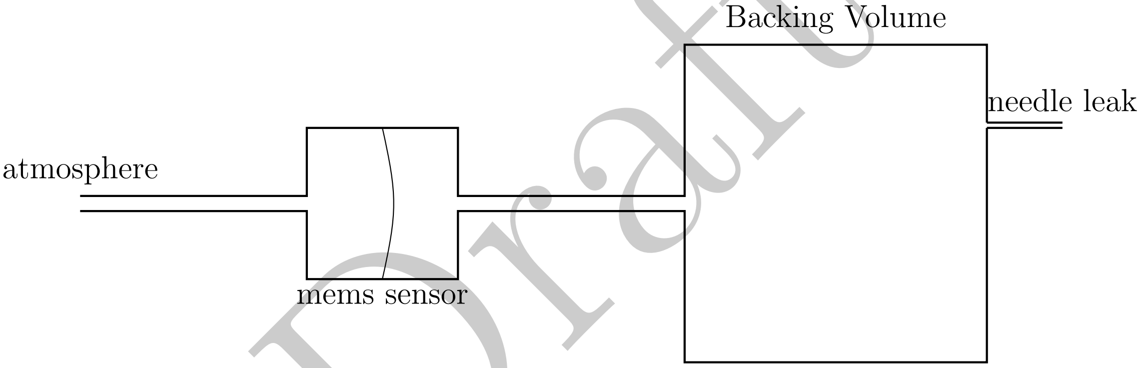


Figure 2: System Overview

5. The Backing Volume



A differential pressure transducer measures difference in pressure between its two ports, one connected to the atmosphere, the other to a sealed container generally known as the backing volume. This backing volume needs a slight, calibrated leak acting to protect the sensor and as a pneumatic filter. Too great a pressure difference due to weather changes may damage the sensor. As the ambient air pressure gradually changes pressure within the backing volume equalises with this via the leak - effectively zeroing the sensor. The leak thus acts as a pneumatic filter, removing very low frequency signals, less than 0.01 Hz caused by atmospheric pressure variation. The aim here being to measure infrasound rather than barometric variation due to the weather.

The backing volume is a hermetically sealed box connected via a tube to the sensor. A fine capillary tube gradually relieves pressure differences between the inside and the atmosphere. A suitable pressure equalisation period of 100-

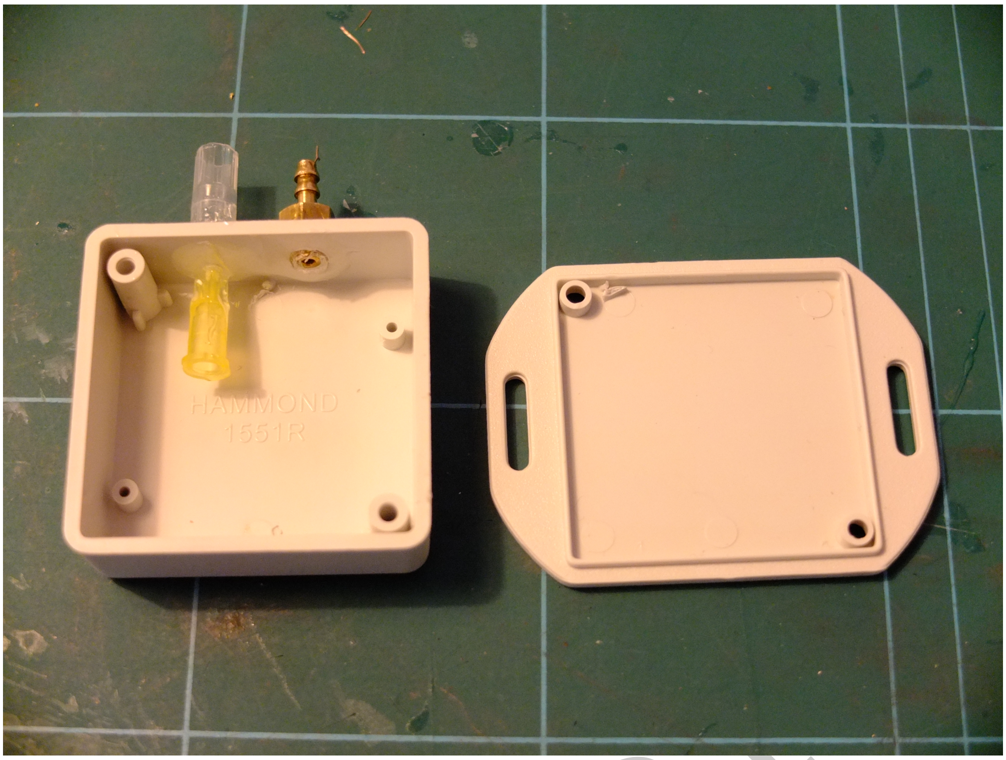


Figure 3: Pneumatic Filter ‘Backing Volume’

200s require the capillary bore and length to be matched with the volume of the enclosure fig 3. This volume & capillary may be modelled as a resistor-capacitor circuit with an acoustic resistance R which may be defined as [5]

$$R = \frac{8\eta}{\pi r^4} l \tag{5}$$

Where r and l are the radius and length of the capillary and η the shear viscosity of the ambient air ($\eta \simeq 1.8 \times 10^{-5} kg m^{-1} s^{-1}$).

Similarly the acoustic capacitance may be modelled as

$$C = \frac{v}{\gamma P} \tag{6}$$

with γ the adiabatic gas constant ($\gamma = 1.40$), v the chamber volume and P ambient pressure.

Thus we may define the backing volume’s time constant, analogous to $\tau = RC$ as

$$\tau = RC = R \frac{v}{\gamma P_a} = \frac{8\eta l v}{\pi r^4 \gamma P_a} \tag{7}$$

We may now calculate the length and radius of a suitable capillary for a given backing volume. Precision capillary tubing may be prohibitively expensive. A fine hypodermic needle (30G, 0.3x13mm), readily available online, glued into a pre-drilled hole in a Hammond 1551RFLGY plastic enclosure has been shown to exhibit a suitable time-constant of 100-150s.

6. The Raspberry PI

The Raspberry Pi is the workhorse of the system. Software has been written in Python which interrogates the mems sensor approximately 40 times per second. These pressure readings are stored every few minutes until midnight when the cumulative day's readings are saved and a new day's recording begun. At intervals (15 minutes in the case of my own systems) two plots , one of raw pressure (Fig 5) and one of acoustic power are generated and saved to disc. These are uploaded to a remote website hourly by a separate crontab script via ftp. The entire system draws about 8 watts and has been left running unattended now for over 2 years. Data is viewed and downloaded for detailed analysis over the Internet.

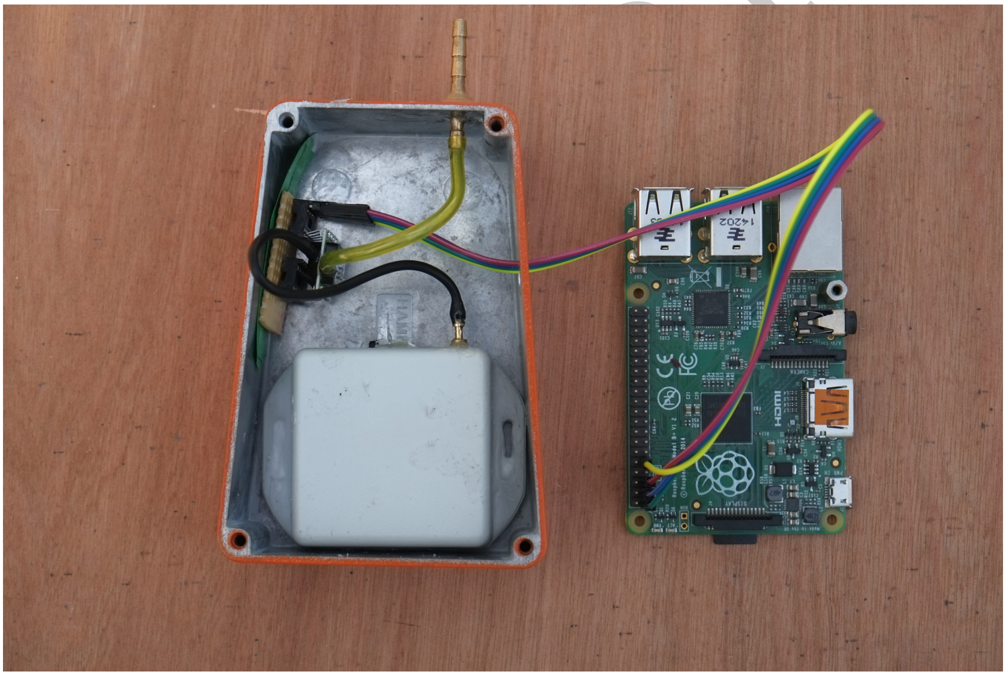


Figure 4: Complete rig no 3

The static device may left in some dusty forgotten corner of a loft-space or outbuilding uploading plots to a website. When some notable event occurs, such as a storm or sonic boom one downloads the raw data file for more detailed analysis.

Data is saved in the geophysics standard *.mseed* format permitting signal analysis using a range of geophysics software. Routines have been written in the open-source python ObsPy suite to facilitate a range of analysis. These may be readily extended by keen students giving a valuable insight into programming and such signal processing techniques as Fourier Analysis. A general purpose Python program has been developed to give students a start on this, figs 8 & 10 .

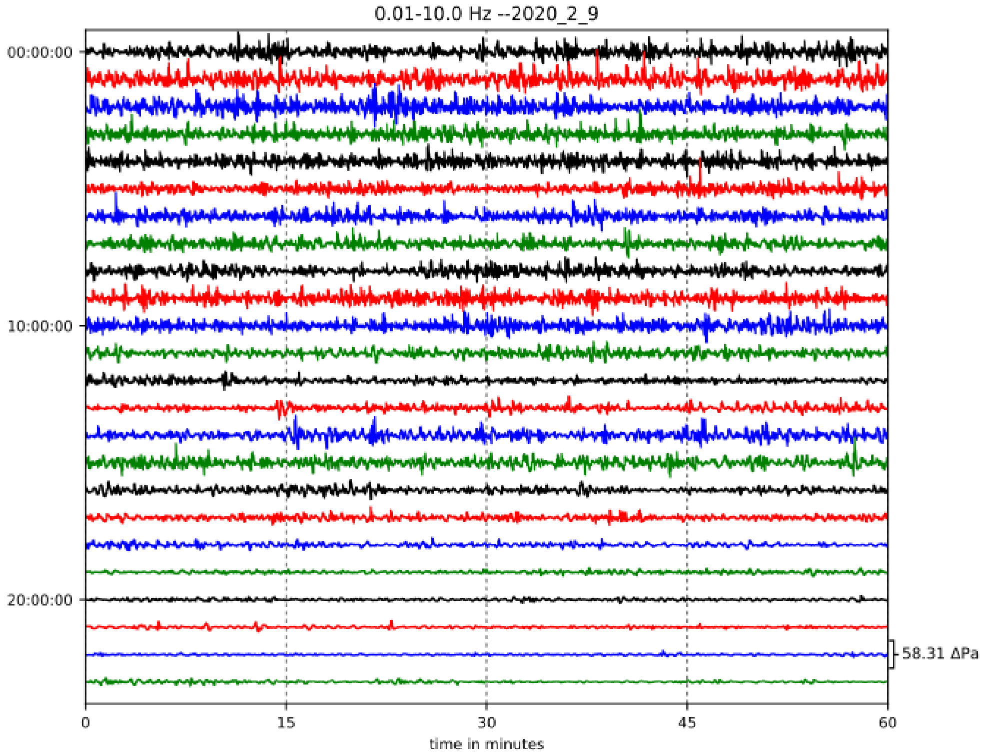


Figure 5: Daily Raw Plot during Storm Ciara

For mobile use the Pi may be powered from a USB power-bank for a day or so whilst a lead acid battery can keep it running for months. As the PI does not have an internal clock a separate, high accuracy real-time clock is included in the design to provide reliable timestamps when the system is powered up without network access such as during field studies.

7. Wind Filter

Local turbulance of wind across the sensor leads to extraneous noise [6] becoming more pronounced at lower frequencies. Some sort of wind-filer is desirable. Many different designs have been investigated - indeed this is ripe for original studies by students. Suitable filters can be though of as averaging local pressure variations across the filter, i.e. random turbulence causing a higher pressure at one part of the filter is likely to be negated by a similarly lower pressure elsewhere whilst the desired low frequency coherent signal is passed.

Common filers include; pipes or porous hose, foam blocks and tents - of the camping variety[7]! Notably missing from literature is the humble loft-space.

A simple loftspace appears to do a good job of reducing noise presumably as localised pressure variations cancel across its large surface. We have had two rigs running since 2018. One in a domestic loft whilst the other is 8m away, outside in the lee of an 8ft fence with a 30cl square foam pond filter acting as both noise and environmental filter. Despite the external rig requiring a 2m hose, of 2mm bore, running from the foam wind-shield it typically records absolute pressure variations almost double those of the loft-space [8]. Differences in frequency response have been observed and will be studied further.

We have tested the use of porous ‘garden sprinkler’ hose. A 20m length was adapted by plugging both ends. From one plug emerges a narrow flexible tube to the sensor head. This can le laid on the ground in a spiral or straight line. Tests on an exposed windy beach indicated that the hose performed better than the foam block at noise reduction.

8. Sample Results

8.1. Wind Turbine

On a blustery day we took readings some 100m from a local wind-turbine using a spiralled 20m porous hose as a wind-filter. Interestingly infrasound levels during the car journey dwarfed those at the site itself Fig 7.

Using the Obspy python routines Saul analysed the signals. Having filmed the turbine he determined a 'blade pass frequency' of 0.75Hz. He could reasonably expect this to be the fundamental frequency f_0 and see signals at this and its harmonics nf_0. After trying various F.F.T. visualisations he did, exactly where predicted except forf_0 which, whilst strong, was masked by noise (note -log scale) Fig 8.

Figure 6: Pond filter tested alongside spiral hose

8.2. Gas Flare

About 5.5 km from the sensor and separated by low hills sits the Olefins No 6 plant on Teesside, a large liquid naphtha cracker. The plant began 'flaring' - burning off gas, at approx 07:25 on 18/7/2017 (video [9]). A clear signal was picked up for the 36 hours of the event. Shown in Fig 9 with the red and blue lines denoting approximate start and end of the flare. The vertical axis shows pressure variation in Pa.

8.3. Helicopter

A Chinook helicopter passed overhead with clear signals picked up by both monitors (loftspace and outside). A simple wavelet analysis shows a clear signal in the 5-12Hz range, with clean sin components at 2-3Hz figs 10 11 .

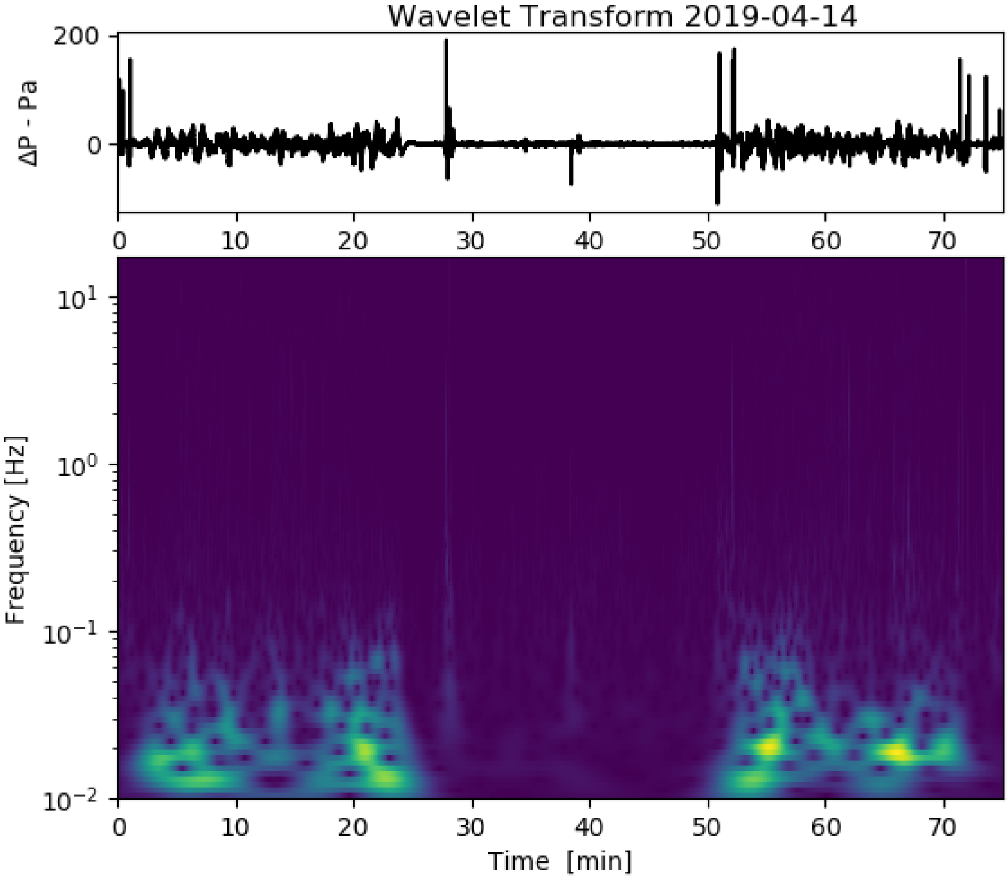


Figure 7: Quiet gap in centre windfarm, either side - car journey

9. National and International Scope

There are few national infrasound networks outside those operated under the aegis of the C.T.B.T.O. Seismometer networks such as IRIS have proved very popular with schools. This is a new field and national networks of infra-sound stations could generate much interest in budding physicists and geologists as well as producing real scientific data.

10. Educational Benefits

Few pre-university science students have direct experience of real science. Projects such as this can combine real science with real-world systems engineering. Students may work in teams to build, test and install rather sophisticated real-time

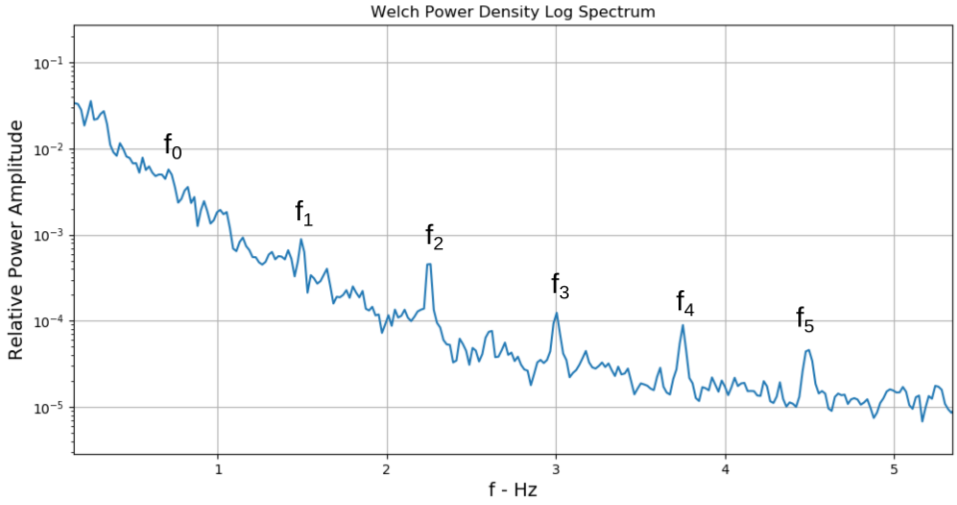


Figure 8: Wind Turbine: f.f.t. showing fundamental and harmonics

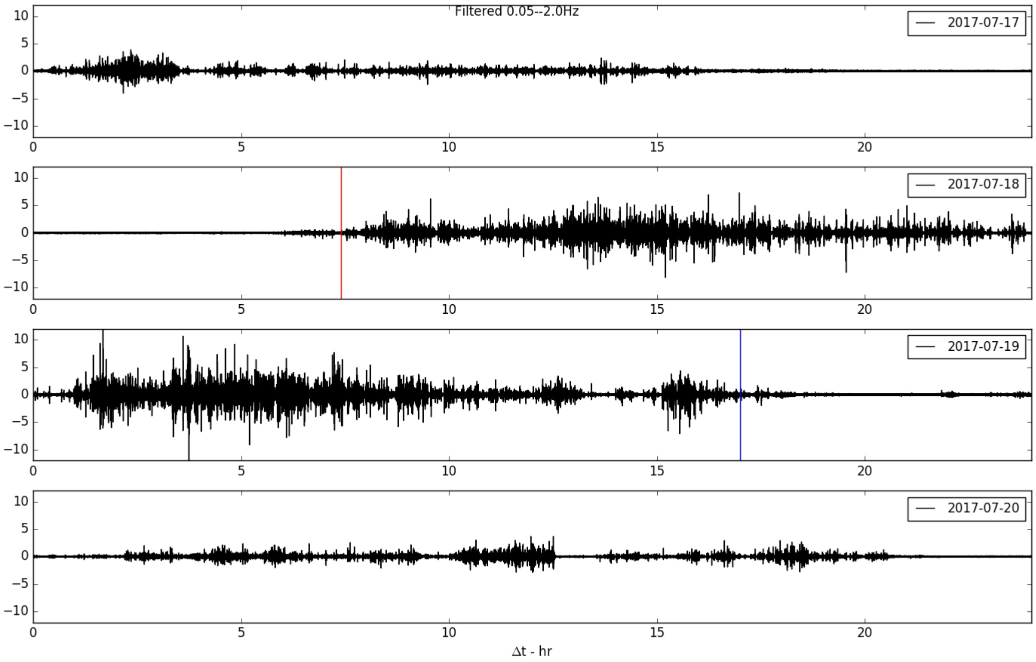


Figure 9: Gas plant flaring 6km away

geophysics monitoring systems. When the initial install is up and running it can them be further developed, different pressure sensors, various wind-shields such as

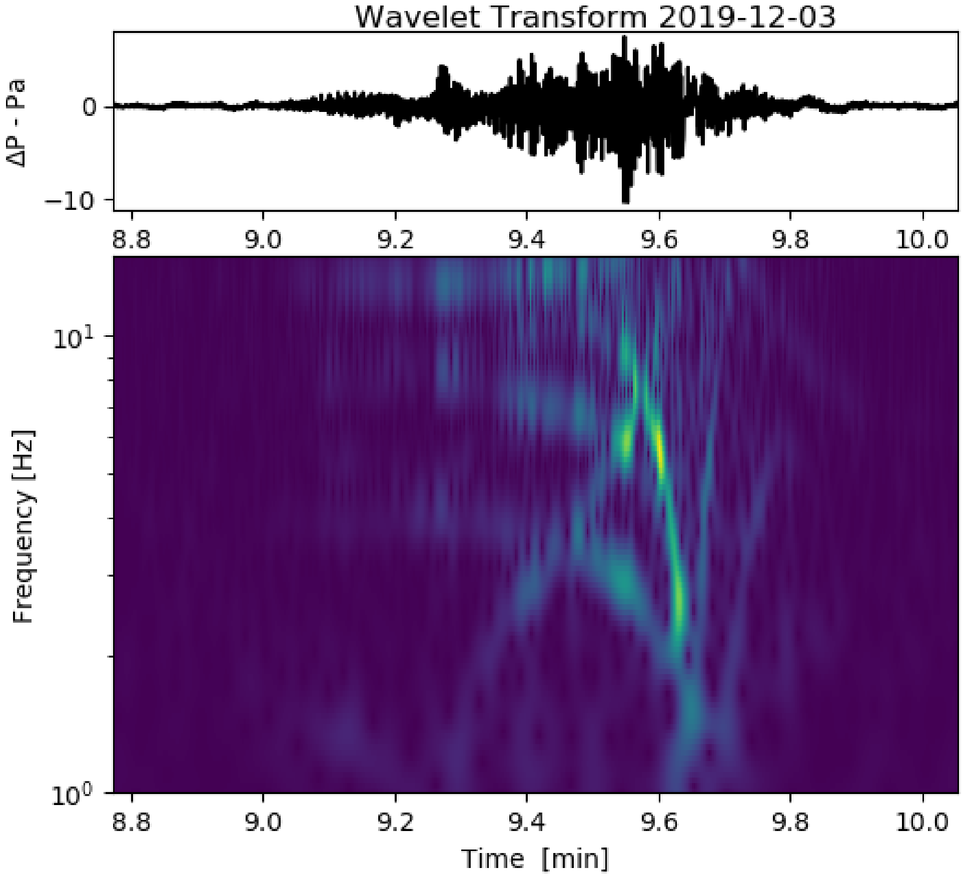


Figure 10: Wavelet transform (f.f.t.) of helicopter approx 200m overhead at 10-12 min and 23-27 min

porous hose may be tested, wireless links between the sensor and base station, statistical filters added to the software. The system is designed this to be sufficiently simple to allow construction by 11-16 yr olds (this has been done) whilst offering sufficient development potential for older students. Students are attracted to the combination of physics, computing and electronics along with space science and geophysics.

Geophysics is under-appreciated, even at A-level despite the stellar career prospects. Projects such as this could stimulate interest in geology, physics and computing.

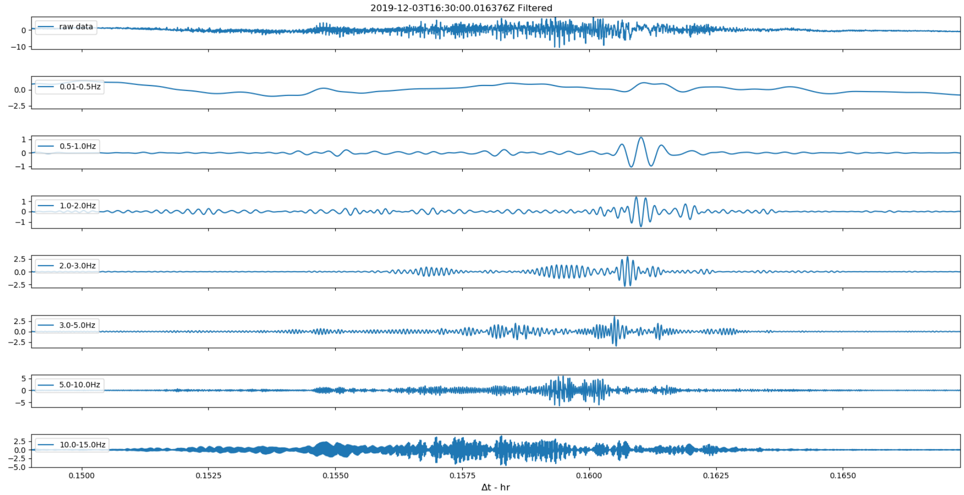


Figure 11: Helicopter Infrasound Power bands

11. Further Information

The hardware costs are small, each sensor rig will cost no more than £100, less if one has a spare P.C. or Raspberry Pi.

Detailed construction instructions and the software can be downloaded from www.starfishprime.co.uk/downloads/downloads.html .

The authors have no commercial interest in this project nor with any equipment suppliers with the project entirely self-funded. Design and code are released open-source.

12. References

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