Listening For Ghost Particles:
The Acoustic Cosmic Ray Neutrino Experiment

Courtney Williams
William Farr C of E Comprehensive School

Supervisors: Jon Perkin, Lee Thompson, Omar Veledar
The University of Sheffield, Department of Physics

Table of contents

1 Introduction to neutrino astrophysics

1.1 Neutrinos

A neutrino (Greek symbol ν, nu) is an extremely light neutral particle that can travel at close to the speed of light and rarely interacts with ordinary matter. Their existence was first postulated by Wolfgang Pauli in 1930 to account for the apparent lack of energy and momentum conservation in beta decay. Neutrinos are leptons, which comes from the Greek word *leptos* meaning light. Incidentally, the word neutrino is a pun on the Italian *neutrone* meaning neutron (Enrico Fermi came up with the name); this is a complete word but *-one* is the Italian suffix for something large. *-ino* means something small, so it simply refers to a small neutral thing!

Electrons are another type of lepton; a table of all six leptons is shown in Fig. 1. There are three generations of lepton, each with a neutrino and an electron-like lepton in it. It has only recently been discovered that neutrinos had a mass at all, but tau neutrinos and tau particles are acknowledged as probably being the heaviest. Naturally occuring leptons generally fall into the first two generations (electron and muon). Sub-atomic particles like leptons have corresponding antiparticles that are the same except they have opposite charges; where this report refers to "neutrinos", it means both neutrinos and antineutrinos.

Neutrinos only communicate via the weak interaction, one of four interactions in the Universe. They are electrically neutral, so the electromagnetic force has no effect; the lack of strong interaction (which binds protons and neutrons in the nucleus) prevents them from being bound into nuclei; and the gravitational force is negligible at subatomic levels. The weak interaction is responsible for radioactive decay, and neutrinos and antineutrinos are products of radioactive beta plus and beta minus decay respectively (see Fig. 2).
Back to top

1.2 The importance of neutrinos in particle astrophysics

Neutrino astrophysics can take us to much higher and previously inaccessible energies and distances, and studying neutrinos could vastly increase our understanding of the Universe. They can travel much further unhindered by interference than radiation or charged particles like protons, because of their neutrality. Their trajectories are very straight and they can pass through even very massive objects like planets or stars with ease. Neutrinos and antineutrinos are by-products of many astrophysical events, so studying them can yield information about these events. Since neutrinos are produced in nuclear reactions, they are produced in stars such as our Sun (basically thermonuclear fusion reactors). They are also produced in supernovae explosions and when neutron stars coalesce. However, these neutrinos have relatively low energies.

Ultra-high energy (UHE) neutrinos are those with energies greater than 10^{10} GeV – eV stands for electronvolt, the amount of energy gained by an electron as it travels across a potential difference of one volt (the equivalent of ~10^{-19} joules). 1 GeV is one gigaelectronvolt, or 10^9 eV. UHE neutrinos would have the same magnitude of energy as a tennis ball being served by Roger Federer; they are produced via the Greisen-Zatsepin-Kuzmin (GZK) mechanism (see Fig. 3), whereby cosmic ray protons interact with cosmic microwave background radiation to produce intermediate particles that decay into neutrinos and antineutrinos. They are also produced when cosmic rays interact with the upper atmosphere.

The very thing that makes neutrinos perfect for detection is the same thing that makes their detection difficult – their lack of interaction with matter as a result of their miniscule mass and neutrality. Though they can travel long distances in space without their trajectories being bent (as would happen to charged particles or light being absorbed and scattered), they can also pass straight through the most massive of objects with ease, thus evading detection. They're not called "ghost particles" for nothing! At this very moment, hundreds of thousands are streaming through every square centimetre of your body, completely imperceptible. It is hypothesised that the Universe is full of very low-energy neutrinos left over from the big bang, which are near impossible to detect. Their estimated density, 10^8 per cubic metre, dwarfs the density of atomic nuclei in the Universe, less than one per cubic metre. Our own Sun emits 2 x 10^{38} neutrinos per second through nuclear fusion at its core; in fact, we emit 400 neutrinos per second due to the radioactive isotopes in our bodies!
Back to top

1.3 Previous methods of neutrino detection

Several methods of detecting neutrinos indirectly have been used in the past. One of these looks at decay products of nuclear reactions involving neutrinos – indeed, neutrinos were first shown to exist in the mid 1950s when Cowan and Reines looked at the reaction of antineutrinos and protons to form neutrons and positrons (both of which can be easily detected; see Fig. 4). Among other things, they received a case of champagne from Pauli for their discovery; he had promised this to whoever was first to detect neutrinos, so certain was he that they would never be found!

Another method involves looking at optical or radio Cerenkov radiation. Optical Cerenkov radiation is caused by particles entering water at speeds exceeding the speed of light in water; a Cerenkov "cone" of intense blue light is produced as the particles slow down (see Fig. 5). Different types of neutrinos give different cones – while the muon neutrino produces a muon and a well-defined Cerenkov cone, the electron neutrino triggers an electron shower with multiple cones and therefore a diffuse Cerenkov cone. This radiation can be detected using photomultipliers, the principle used by detectors such as the Sudbury Neutrino Laboratory and SuperKamiokande. Radio Cerenkov radiation is generated when neutrinos interact with ice and charged particles are created. Radio pulses are emitted, which can be detected – this is the principle behind the RICE and ANITA experiments. The limit of optical Cerenkov detection is approximately 10^7 GeV; radio Cerenkov detection can look at particles with energies of up to 10^9 GeV.
Back to top

1.4 Acoustic detection and ACoRNE

Acoustic detection is superior to previous methods because previous methods have been unable to detect neutrinos with energies in the order of 10^{10} GeV and these UHE neutrinos are particularly interesting from an astrophysical perspective. Their flux (or rate of flow) is one thing that will be measured, to see if it fits in with the Standard Model of particle physics. Observing them would also help to determine the origin of UHE cosmic rays. One advantage of the acoustic detection method is that the attenuation length of the acoustic pulse from a cosmic ray shower of neutrinos is in the order of tens of kilometres, meaning the sound can be recorded from kilometres away and setting up detectors can be done relatively cheaply. As acoustic detectors are built in water, there are fewer restrictions on where they can be built. Large volumes of water are needed to be in with a chance of detecting even a few neutrinos.

The ACoRNE (Acoustic Cosmic Ray Neutrino Experiment) collaboration has secured funding to use an MoD hydrophone array off the coast of Rona in North-West Scotland (location indicated in Fig. 6). A hydrophone is like an underwater microphone and at Rona they are being used to detect neutrinos acoustically. When a neutrino interacts with the seawater it releases energetic particles. This energy heats the seawater very rapidly and produces a characteristic bipolar acoustic pulse in the frequency range 20-30kHz, which a hydrophone then detects. It is hoped that this method will allow the detection of UHE neutrinos, which have never been detected before.

The Rona array consists of eight hydrophones, though usually number eight is non-functional. They cover an area of around 200m by 1500m and are at a depth of 100m (the trench they are situated in is 200m deep). A scale diagram of their relative positions is shown in the appendix. The hydrophones record frequencies up to 70kHz (so sample at 140kHz, twice the maximum frequency of the signal) and sampling at 16 bits. Each hydrophone takes a sample every ten minutes, producing ten-minute sound files, and they have been doing this since December 2005. This amounts to around 28 terabytes of data in total. 1 terabyte is 10^{12} bytes – to put this is perspective, the memory stick this report is stored on can hold 2GB (2 x 10^9 bytes), so the Rona data would fill up 14,000 memory sticks. Luckily, much of it has already been deleted and the remaining data compressed using FLAC (Free Lossless Audio Codec).
Back to top

1.5 Applications of ACoRNE

Besides particle astrophysics, ACoRNE has many other potential applications (one of which will become clear upon reading my report). Its original purpose was to detect UHE neutrinos in order to increase our knowledge of the Universe on both a subatomic and cosmological scale – despite what some people might think, this is a perfectly satisfactory and noble endeavour. However, the ACoRNE collaboration hopes to develop the hydrophone array (originally used by the MoD to listen for submarines) for three other purposes.

The first of these concerns climate change (and is therefore likely to attract funding). It is possible to monitor temperatures in the sea by transmitting acoustic signals and detecting them again from a large distance – the collaboration can use its knowledge of signal processing (perhaps including the work I did on the second task given) to develop this technique. The second involves studying rainfall – since a lot of the UK's weather originated over the Atlantic Ocean and land-based study only works up to a point, acoustic detection at sea could solve the problem and aid forecasting, as well as help to produce global climate models. The final application is the tracking of marine species (this is the one that the first section of my project was concerned with). This could help us to understand the effect of active sonar on dolphins and whales (so as to avoid another mass beaching like the one that occurred near Falmouth), and the system would be quickly deployable so you could just throw it in the sea and start taking measurements. This could also be applied to other areas of related study, such as migration patterns and echolocation mechanisms.

[Back to top]

2 The effect of biological noise on data from the Rona hydrophone array

2.1 Research into use of echolocation by odontoceti

One of the problems with underwater acoustic detection is the presence of biological noise. Dolphins and other cetaceans have the ability to locate objects using a technique called “echolocation”. Fig. 7 shows the physiology that enables them to echolocate, which is useful when searching for food in low visibility conditions such as those found in the waters around Rona. It is also useful that sound travels 4.5 times faster in water than in air. The sound is produced in the nasal cavity and the fatty “melon” focuses the sound. If the frequency of the dolphin’s click matches the resonant frequency of the fish’s gas bladder, the two waves will interfere constructively and the dolphin will receive the amplified signal telling them that a fish is nearby. Around 90% of the reflected sound is the echo from the fish’s gas bladders. The hydrophones at Rona record this sort of noise in addition to pulses from neutrinos.

Odontoceti active around Rona include:

- Common porpoise
- Northern bottlenosed whale
- Orca/killer whale
- Sperm whale
- Striped, common, bottlenosed and white beaked dolphins

[Back to top]

2.2 Appropriate selection of data to be analysed

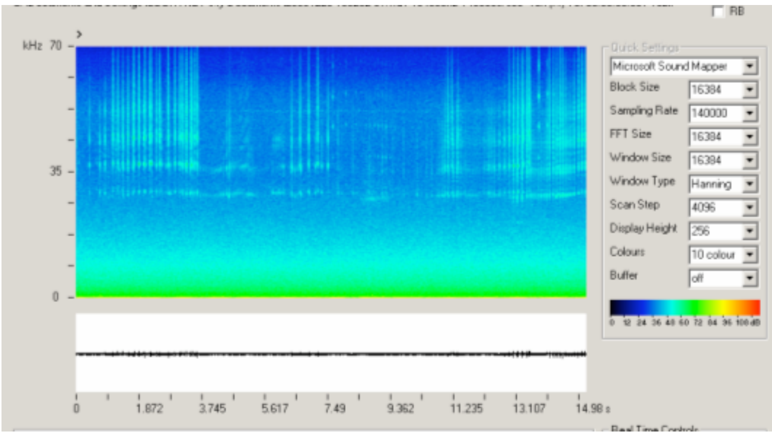
Because of the volume of data from Rona, it is imperative to select samples carefully to obtain meaningful results when searching for biological noise. There are a number of ways to do this.

- Around 40% of the files from Rona are either saturated or contain no signal (see Fig. 9) – using SeaPro these can be recognized easily, but as a rule of thumb unusually large or small files should be avoided.
- We know that dolphins feed around dusk and dawn, so can use sunrise/sunset times to sample files that are more likely to contain clicks.
- Some of the hydrophones are closer together than others (see scale diagram in appendix), so it would be just as effective to analyse data from just three of them at a time. For example, I used 2/4/6 where possible rather than, say, 1/2/3.

[Back to top]

2.3 Use of SeaPro to identify clicks

SeaPro (Sound Emission Analyser) makes it possible to see the spectra of sound present so clicks are easily recognised and files can be searched through quickly. Sound files can be played and analysed simultaneously at various speeds, or the entire file can be analysed at once so it can be browsed through. Screenshots can also be taken of the spectra. In effect, it gives a three-dimensional view of a sound file; time is plotted along the x-axis, frequency along the y-axis and amplitude is represented using a scale of black & white or colour intensity. The trace below shows dolphin clicks, which can be easily identified (they are the light blue lines superimposed on the darker background – they occur at in the approximate frequency range 25–70kHz). Though the SeaPro window gives a scale relating the colour to a decibel value, this is not to be taken as quantitative – it simply gives an indication of relative amplitudes.



Using SeaPro, the positions of 100 individual clicks within 11 files were sampled. This large sample size was chosen to ensure a wide range of results and greater reliability; basic statistical theory states that a large sample is more conducive to reliability than a small sample. Originally, 897 files were chosen to sample using the parameters laid out in section 2.2. The files were taken from three specific time frames: dusk, dawn and night time, as these times are when odontoceti are most likely to be active and hunting. They were also taken from different times of the year. 9 samples were taken for each time – from 3 different hydrophones (the combination being either 2/4/6, 1/4/5 or 3/4/7 so the whole area of the array was covered) and 3 consecutive time frames covering 30 minutes in total. Files were then chosen at random and searched until 100 clicks had been found. Time signatures of clicks were noted down, and screenshots of any particularly interesting traces were taken.

[Back to top]

2.4 Use of Matlab to analyse clicks further

Matlab is a computing language and environment that allows the user to (among other things) analyse sound files. Having identified 100 clicks, Matlab was used to plot a time versus relative amplitude graph, then zoom in on each individual click (i.e. to isolate the click so the minimum amount of background noise is included). A power spectrum for each click was obtained; this shows which frequencies have the highest relative amplitude. Matlab functions can be found in the appendix 6.2, and Fig. 10 shows the process of zooming in on a click and producing its power spectrum.

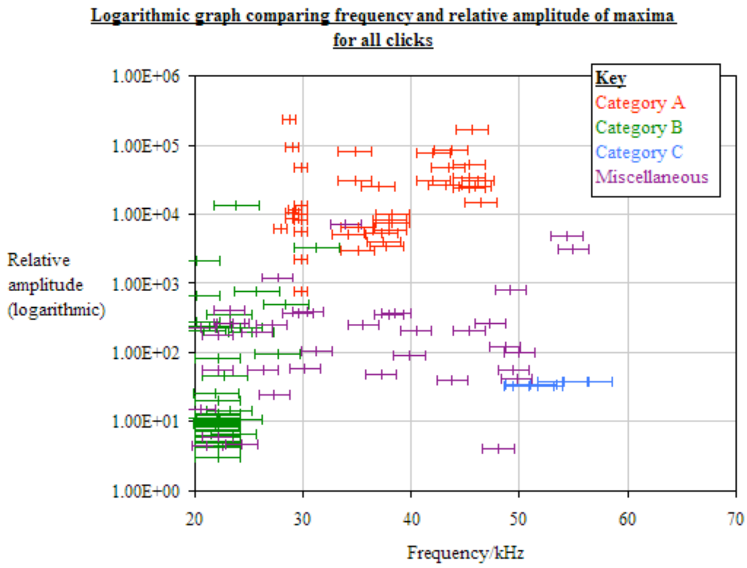
All 100 samples were analysed. Extraneous samples were analysed as well and discarded when their power spectra revealed them to be either background or mechanical noise (see Fig. 11). CSV files were written for each data set using Matlab commands; these contained the amplitude of the spectrum at each frequency step.
Back to top

2.5 Analysis of frequencies where peaks occur

After using Matlab to obtain power spectra for clicks, it was necessary to analyse the data and thus find out the frequency values for the maxima. Though Matlab is a powerful tool it was not appropriate for the task in hand due to the lack of capacity for synchronised data analysis – that is, only one set of values can be loaded at a time. It also only reads the maximum value and analysing peaks in a power spectrum requires complex programming. Instead, Microsoft Excel was used as this is more familiar and easier to manipulate. The 100 samples were first organised into rough groups according to their shapes and with roughly similar peaks. These groups (and the number of samples in each group) were:

- A: three major peaks – approx. 30kHz, 37.5kHz and 45kHz (11)
- B: peak at 20-25kHz, decrease with increasing frequency (45)
- C: broad peak (not sudden increase) at 50-55kHz (5)
- D, miscellaneous: the graphs that didn't fit into A, B or C (38)

The following graph shows all the results, plotting frequency against relative amplitude with error bars of one standard deviation for each individual data set; separate graphs can be found in the appendix.



Back to top

2.6 Relation of findings to theory and conclusion

The graphs produced showing the peak frequencies of the clicks and the samples themselves demonstrate a few things.

Click spectra were not all that similar, so the noise may be either anthropological or subject to interference. The greatest concentration of peaks occurs at lower frequencies and there are no peaks after 60kHz. Since dolphin clicks usually exceed this value for frequency at the very least, it is likely that dolphins aren't to blame for the noise. The distribution of the clicks doesn't resemble the usual click train for a dolphin; instead, it resembles the click train of a whale, where individual clicks are isolated. The concentration of frequency maxima at lower frequencies (i.e. around 20kHz) indicates that whales could be responsible for the noise. Unfortunately, these are the same sorts of frequencies that neutrino pulses are at!

I had a few theories concerning the type of whale present. At first I thought they were sperm whales, until I found that they echolocate at frequencies of only a few Hz (too low to be recorded by my data, and probably lost amidst the low frequency wave noise). Minke whales were another possibility, but they too click at low frequencies. In fact, minke whales are baleen whales, so don't echolocate at all! Then I considered false killer whales, which do echolocate at the frequencies my data show, until I discovered that they stay in deep water as opposed to the area where the array is, which is only 200m deep. Finally, I have come to the conclusion that the animals could be killer whales – they operate at frequencies of 0.5-40kHz (with peaks at 6-12kHz, which might account for the low relative amplitude of many of the click maxima) and are common in the area. However, the difficulty in obtaining samples of clicks shows that the problem is not that extensive. A few samples of daytime recordings were taken, which contained few or no clicks – this demonstrates the idea that odontoceti are active at night, dawn and dusk.

In conclusion, most of the biological noise around Rona is due to whales rather than dolphins, but even this noise doesn't corrupt the data too much.
Back to top

2.7 Evaluation and possible further investigations

The sample size was 100 – this led to fairly reliable results and the samples were selected carefully from a population of thousands of hours of recordings. However, further sampling would only improve the reliability of the sample and this would be a natural progression. Since this can be carried out remotely, I would be happy to do some of this myself after the placement draws to a close.

It is essential for us to only look at the files that are most likely to contain clicks, if only to cut down on the workload. There are thousands of hours of recordings and data acquisition still continues – the methods previously mentioned for reducing the number of files should be taken advantage of to provide results efficiently. However, further investigation would mean that more files within the parameters laid out in 2.2 could be analysed.

The hydrophones only record up to 70kHz, so a lot of noise due to echolocation isn't even registered. The sound of waves has proved to be a bigger problem, especially since the hydrophones are only 100m from the surface (the trench they are situated in is 200m deep), so this is also a potential topic for study. Recording above 70kHz is of little interest to ACoRNE, but it could be of interest to those researching bioacoustics or odontocete behaviour. It may be possible to install a "pinger" device at the array to stop animals getting injured or damaging the equipment; however, this technology is still in its infancy and might not even make a difference.

Snapping shrimp have been shown to be the noisiest animals in the sea and they have already proved problematic for ACoRNE. We could use studies done by marine biologists to inform our study of neutrinos and improve our data collection and analysis. In return, we can show them our results pertaining to frequency maxima of odontocete clicks!

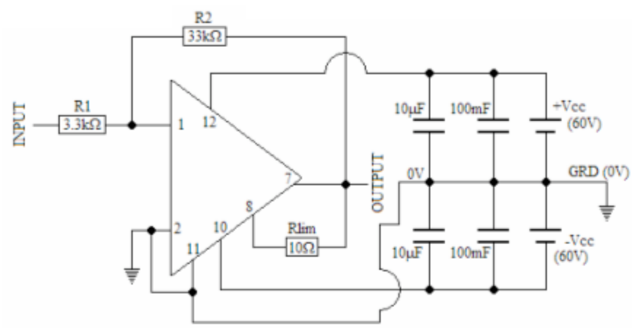
Finally, a real boon would be the automation of data acquisition using Matlab. Using Excel was appropriate for a beginner at Matlab, but in the long run Matlab is the superior piece of software. As Matlab licenses are very expensive and free trials not available to students, I have been experimenting using Scilab. This is very similar to Matlab, but has the advantage of being free – you might say that Scilab is to Matlab what the Hitch-hikers Guide to the Galaxy is to the Encyclopaedia Galactica, minus Don't Panic being written in large, friendly letters on the front.
Back to top

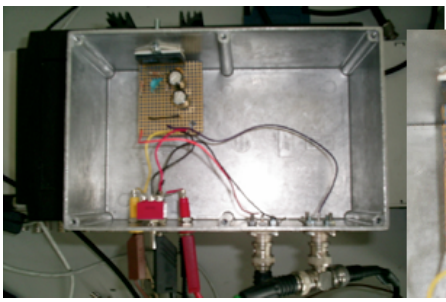
3 A study of hydrophone response to simulated acoustic neutrino pulses

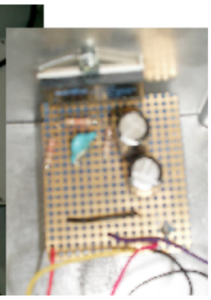
3.1 Introduction to acoustic neutrino pulses
When UHE neutrinos react with water, an acoustic pulse is given off. This can be used to detect the particles indirectly. The neutrino's reaction with the water triggers the production of other energetic particles and their energy heats the water instantaneously. The acoustic pulse is bipolar in shape (see Fig. 12) and is in the frequency range 20-30kHz. It gives us information about neutrino flux and energy and can allow us to look at higher neutrino energies than previous detection methods have allowed.
Back to top

3.2 Simulating acoustic pulses in the lab
ACoRNE uses hydrophones to detect these pulses, and Sheffield has its own water tank where simulation of neutrino pulses can take place (see Fig. 13). It has two hydrophones, one of which is a transmitter and the other a receiver (see Fig. 14). Three different pulses were generated – a 10kHz bipolar, a 23kHz bipolar and a 23kHz filtered sine wave – and they are shown in Fig. 15. This is all done by computer, though the position of the hydrophones must be changed manually. The task in hand involves trying to find the gain limit for the voltages of pulses going into the hydrophone, after which linearity between gain and voltage of received signal (in other words, input and output) is no longer preserved.
Back to top

3.3 Building a power amplifier
It was necessary to build a power amplifier because the voltages of the pulses generated by the computer are too small. The amplifier has a gain of 10, meaning it increases these voltages so they are ten times as high when they are sent to the transmitting hydrophone. It will also be used when the group travels up to Rona to carry out tests at the ACoRNE site, so it had to be sturdy enough to withstand being on a boat. The external controls are all on the front (rather than the side or back) for ease of use. A schematic diagram and photo of the amplifier are shown below. The amplifier gives a gain of –R2/R1, or -33/3.3, which equals -10. The minus sign inverts the signal in the y-axis.







Back to top

3.4 Methodology of experiment
Three parameters were varied: the frequency of the pulse (either 10kHz or 23kHz), the shape of the pulse (bipolar or sine wave – only one frequency of sine wave was used, 23kHz) and the distance between the hydrophones (14cm, 18.5cm, 27cm and 35cm). The input variable was gain (the amplitude of the generated signal), and values for gain were between -1 and -5. Fig. 15 shows the three pulses generated, while Fig. 16 compares transmitted (yellow) and received (pink) pulses. The second trace shows that the limit for linearity has been exceeded, as the received pulse no longer resembles the transmitted pulse/

- A pulse is generated on the PC using National Instruments LabVIEW.
- The pulse is amplified by the power amplifier (which uses a power supply of 75V) so it is ten times as strong.

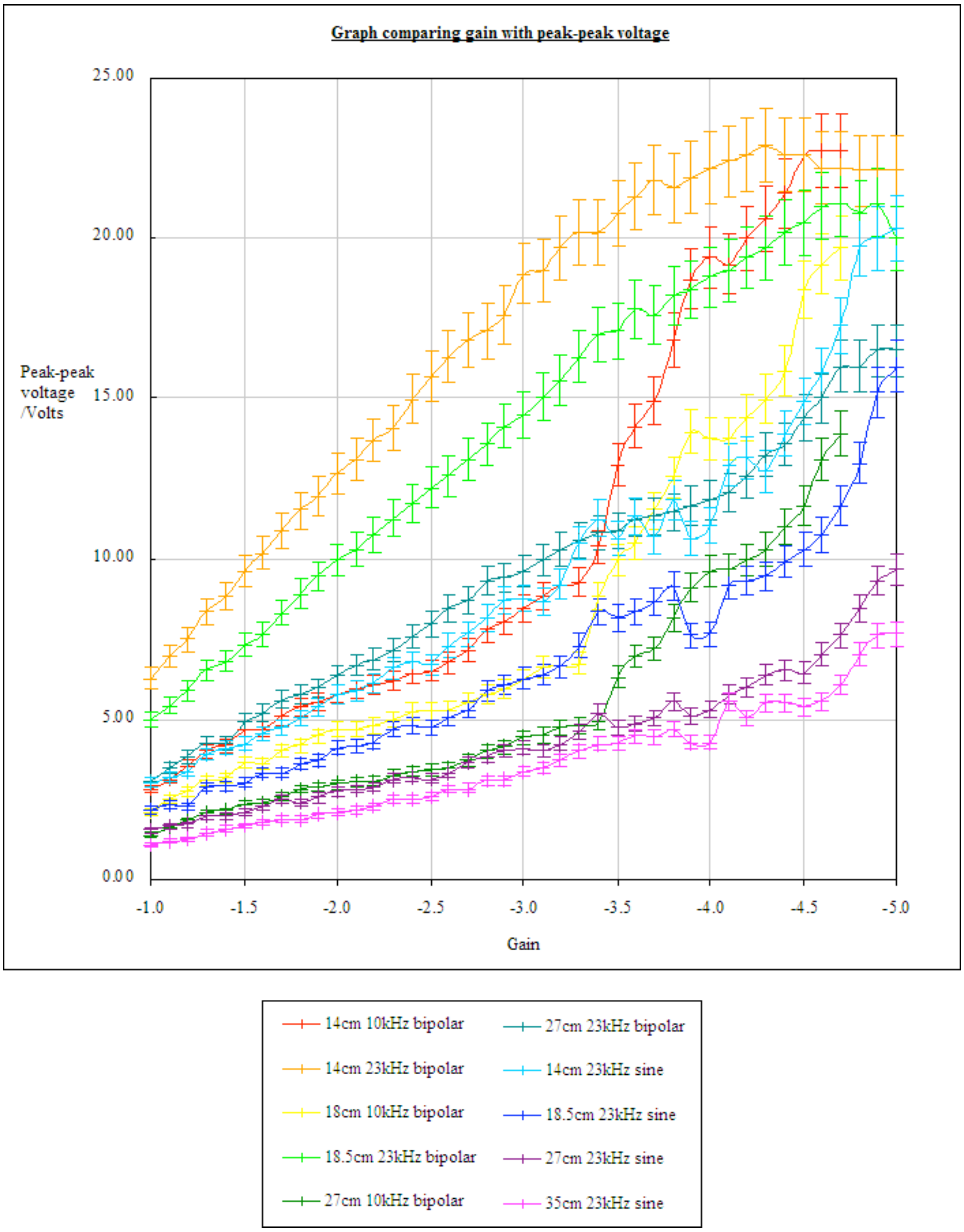
- The pulse is sent to the transmitting hydrophone, which sends out a signal.
- The pulse is received by the receiving hydrophone.
- The pulse is fed into a conditioning amplifier, before it is sent to an oscilloscope.
- Values for peak-peak, maximum and minimum voltages are taken, and the waveform is saved as a Matlab file.

A photo of the equipment used is shown below (a sine wave is being generated).

[Back to top](#)

3.5 Analysis of results

The graph over the page shows how frequency and distance affect the peak-peak, minimum and maximum voltages of the signal received by the hydrophone, with error bars of 5%. Separate graphs and the raw data are shown in the appendix.

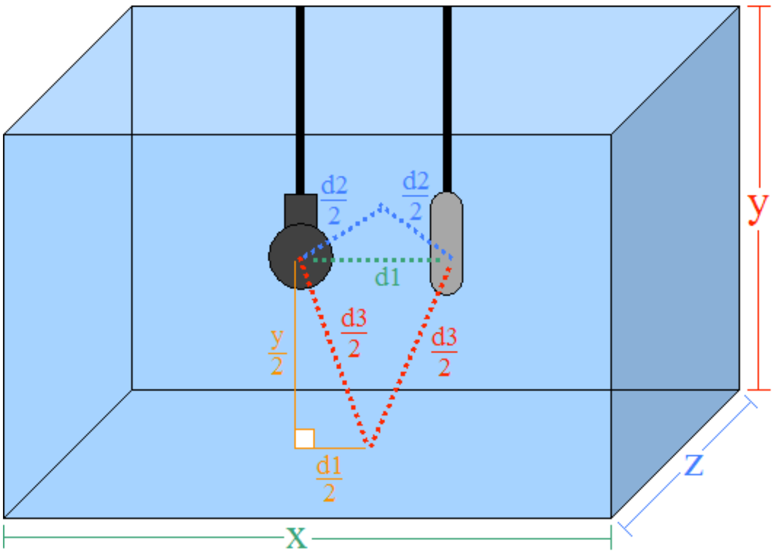


My results demonstrate linearity between gain and peak-peak voltage at first, which was expected. The gain limit for all the pulses is -3.3, which is indicated by the fact that all the graphs become non-linear at this point. For the 23kHz pulses, the non-linearity after -3.3 is much less erratic. The graph also shows that, as expected, greater distances diminish the voltage of the received signal.

Back to top

3.6 The effect of reflections from the side and bottom of the tank

As this experiment utilised a relatively small volume of water within a glass tank, the sound produced by the transmitting hydrophone will have inevitably been reflected off the sides and bottom. To work out when these reflections occur we can use Pythagoras' Theorem and the equation time = distance/speed. We know that the speed of sound in water is around $1500ms^{-1}$. The diagram below shows how Pythagoras' Theorem was used to work out the distances travelled by the sound reflecting off the side of the tank, and thus the time taken. Distances originally measured in centimetres have been converted to metres for ease of calculation. The "E-6" in the time columns indicates that the values are in microseconds (i.e. 10^{-6}s).



$$(^{d3}/_2)^2 = (^{y}/_2)^2 + (^{d1}/_2)^2$$

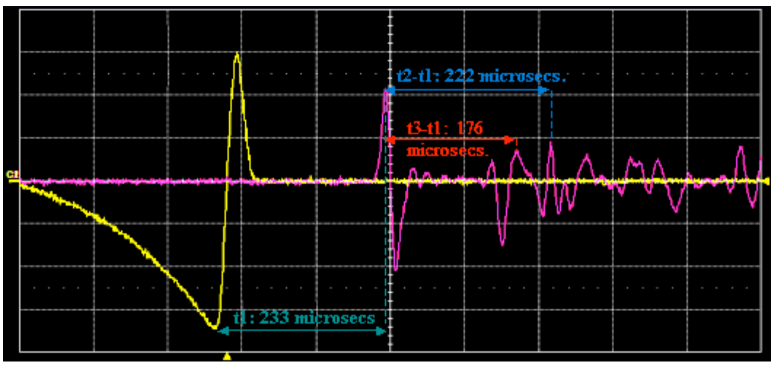
$$^{d3}/_2 = \sqrt{(^{y}/_2)^2 + (^{d1}/_2)^2}$$

$$d3 = 2\sqrt{(^{y}/_2)^2 + (^{d1}/_2)^2}$$

	x	y	z
dimensions (m)	1.50	0.505	0.587
dimensions/2 (m)	0.750	0.253	0.294

d1 (m)	t1 (s)	d2 (m)	d2-d1 (m)	t1-t2 (s)	d3 (m)	d3-d1 (m)	t3-t1 (s)
0.14	93E-6	0.603	0.463	309E-6	0.524	0.384	256E-6
0.185	123E-6	0.615	0.430	287E-6	0.538	0.353	235E-6
0.27	180E-6	0.646	0.376	251E-6	0.573	0.303	202E-6
0.35	233E-6	0.683	0.333	222E-6	0.614	0.264	176E-6

The image below is the trace for a 23kHz bipolar wave with a gain of -3 at a distance of 35cm. Each horizontal section has a value of 100µs, and the arrows are scaled to represent the amount of time predicted for the reflections by my calculations (notice that for the distance d1, the peak is inverted in the x-axis – "upside down"). While the calculations are correct, there has also been a lot of interference caused by the extra distance travelled through the water. It is easy enough to scale the window to discard reflections, and the larger the volume of water the less the problem will occur. Even at this level, the reflections don't corrupt the results.



Back to top

3.7 Relation of findings to theory and conclusions

The simulated bipolar pulses can be thought of as analogous to those that would be triggered by neutrinos, so the hydrophone response to these is an important topic of study. It has been demonstrated that the gain limit for the hydrophones is -3.3, which will guide the ACoRNE collaboration when they work at the Rona array.

Back to top

3.8 Evaluation and possible further investigations

As computers controlled the experiment the outcome is likely to be very accurate and hence reliable. The error bars are due to the fact repeat measurements were not taken – they were not required as the computer gave off consistent signals and results that were taken more than once were all very close or equal to the original results.

The natural progression of this experiment is to a larger volume of water, such as a pool or lake, leading eventually to tests being carried out at the ACoRNE site. This would gradually decrease the influence of reflections on the results. We could even try to generate noise like those from odontoceti to look at how the hydrophone responds. If a pinger device were to be installed at Rona, we would have to find a way to calibrate the hydrophones so the sound isn't registered. Again, this would start in the lab and progress upwards, but before testing it in open water we would have to work with marine biologists to ensure it wouldn't be damaging to any animals in the local habitat.
Back to top

4 References

4.1 Text references

ACoRNE Collaboration, The (2000). *The ACoRNE Proposal*.
Web site: http://www.pppa.group.shef.ac.uk/acorne/pdf/proposal.pdf

Busch Entertainment Corporation (2008). *KILLER WHALES: Communication & Echolocation*. Retrieved Aug 29, 2008, from SeaWorld/Busch Gardens.
Web site: http://www.seaworld.org/animal-info/info-books/killer-whale/communication.htm

Close, F (2006). *The New Cosmic Onion: Quarks and the Nature of the Universe*. Boca Raton, Florida: Taylor & Francis.

Centre for Whale Research (2007). *How do Killer whales locate food?* Retrieved Aug 1, 2008, from The Centre for Whale Research.
Web site: http://www.whaleresearch.com/thecenter/Facts002.html

Cottis, R (2002). *Wildlife on Rona*. Retrieved Aug 1, 2008, from The Isle of Rona.
Web site: http://www.isleofrona.com/wildlife.htm

Danaher, S et al (2008). *Acoustic sensor development for the monitoring of climate change, environment and biological species*. (This was given to me by Dr Lee Thompson and has yet to be published)

Nave, R (2008). *Cerenkov Radiation*. Retrieved July 22, 2008, from HyperPhysics.
Web site: http://hyperphysics.phy-astr.gsu.edu/hbase/relativ/einvel.html#c3

Norton, A (2005). *How the Universe Works*. Milton Keynes: The Open University.

Perkin, J (2005). *Diving for Neutrinos*.
Web site: http://www.pppa.group.shef.ac.uk/acorne/pdf/JP-LLWI2005.pdf

Thomas, J et al (2004). *Echolocation in Bats and Dolphins*. London: The University of Chicago Press.

Thompson, L (2006). *Prospects for the detection of ultra-high energy neutrinos*.
Web site: http://www.pppa.group.shef.ac.uk/acorne/pdf/LT-CosmicParticles2005.pdf

Thompson, L (2008). *The ACoRNE Project: Listening for Neutrinos*.
Web site: www.physics.ox.ac.uk/APP2008/talks/Lee_Thompson.ppt

Waters, D (2004). *Acoustic Detection of Ultra-High Energy Neutrinos*.
Web site: http://www.pppa.group.shef.ac.uk/acorne/pdf/DW-IOP2004.pdf

Waters, D (2005). *Neutrino Astronomy*.
Web site: http://www.hep.ucl.ac.uk/~dwaters/acoustic/neutrinos_wcp_18.02.05.pdf

Sunrise and sunset data for Edinburgh from *www.timeanddate.com*, © 1995-2008 Steffen Thorsen/Time and Date AS. Retrieved July 22, 2008.
Web site: http://www.timeanddate.com/worldclock/astronomy.html?n=304
Back to top

4.2 Picture references

Fig 3 – adapted from Waters (2005)
Fig 5 – http://hyperphysics.phy-astr.gsu.edu/hbase/relativ/imgrel/cerenkov.gif
Fig 6 – http://www.scotland-inverness.co.uk/scotlandmap.jpg, reproduced from Ordnance Survey map data by permission of Ordnance Survey, © Crown copyright.
Fig 7 – adapted from http://www.whaleresearch.com/images/echolocation.jpg (courtesy Kelley Balcomb-Bartok/All Rights Reserved)
Fig 8 – http://www.isleofrona.com/Dolphin%20No%201.JPG
Fig 12 – adapted from ACoRNE Collaboration (2000)
Back to top

5 Acknowledgements

I am grateful to the Nuffield Foundation for funding this project, as well as Kevin Cumpsty and Paula Bailey for securing additional funding and assisting me with my placement. Thanks to the Department of Physics at Sheffield for accommodating me, and also the Science department at William Farr for their support. Finally, I wish to thank my supervisors Jon Perkin, Lee Thompson and Omar Veledar for their help and patience, and for making my six weeks at the university productive and enjoyable.
Back to top

6 Appendices

6.1 Matlab functions

plotWavFile.m (J Perkin) – This function plots time against relative amplitude (±), so is useful for finding the exact time signature of a click – spectra can be zoomed in on. The file is analysed between two specific times (t1 and t2); the time interval must be fairly small (the maximum interval used was 10 seconds) so clicks can be easily identified and Matlab doesn't crash because it is trying to analyse a huge chunk of data. Fs, the sampling frequency, is also defined.

```
function [x,y,Fs]=plotWavFile(filename,t1,t2)

>> Fs=140000;
>>
>> if(t1==0)
>>     [y] = wavread(filename,[1,Fs*t2]);
>>     x=[1/Fs:1/Fs:t2];
>> else
>>     [y] = wavread(filename,[Fs*t1,Fs*t2]);
>>     x=[t1:1/Fs:t2];
>>
>> end

plot(x,y);
```

plotWavSpectrum.m (C Williams, J Perkin) – This plots the power spectrum of the sample – that is, frequency against relative amplitude (+). It does this by calculating the 512-point fast Fourier transform (which basically involves breaking a complex wave down and expressing it as a sum of sinusoidal components – very useful in sound analysis) of a signal to get Y, then obtaining the power spectrum Pyy by multiplying Y by its complex conjugate (making all the values positive) and dividing by 512. The first 257 points are plotted on the frequency x-axis.

```
>> function [f,Pyy]=plotWavSpectrum(y,Fs);
>>
>> Y = fft(y,512);
>>
>> Pyy = Y.* conj(Y) / 512;
>>
>> f = Fs*(0:256)/512;
>>
>> plot(f,Pyy(1:257))
```

Example of code used to produce CSV file:

```
>> [x,y,Fs]=plotWavFile('20051223-185232-01.wav',215,225);
>> range = get(gca,'XLim')
```

[after zooming in this command returns the range of max/min x values of the new graph]

```
>> range =

217.2760 217.2793

>> [x,y,Fs]=plotWavFile('20051223-185232-01.wav',217.2760,217.2793);
>> [f,Pyy]=plotWavSpectrum(y,Fs);
>> csvwrite('20051223-185232-01-217.2760-217.2793.dat',Pyy)
```

[i.e. filename is 'yearmonthday-hourminutesecond-time1-time2.dat'; this creates a CSV file that can be analysed in Excel – I decided on and wrote this command myself]

Back to top