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Square Kilometre Array

Level 8

Science

First published June 2011
Ministry of Economic Development
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This resource has been produced to support the delivery of the New Zealand Curriculum, with funding from the New Zealand Government, through the Ministry of Economic Development.

Introduction

This resource has several student science activities reinforcing aspects of the 'big idea' in astronomy: that everything we know about the universe is from "messages" in the electromagnetic radiation we receive from beyond planet Earth.

The activities at this level are part of a series for Years 7–13 (up to Level 8). If your students had not experienced the earlier activities a selection of them would be a useful introduction to the 'big idea'.

The previous activities in this series included how common devices encode messages in light, exploring wavelengths of light, the properties and behaviour of waves, using radiation to measure temperature, colour temperature, detecting radio signals, using directional aerials, direction finding, random signals, noise cancellation, aerials for different signals, etc.

The activities support some Achievement Standards:

	Activity						
NZQA standards	1	2	3	4	5	6	7
90520	×	×	×	×	×	×	×
90523					×		
90774							×

The Level 8 student activities

These activities introduce several 'big ideas'.

1. CD spectrometer and measuring wavelengths.
2. Make and use a directional aerial.
3. Young's double slit at radio frequencies.
4. Spectral analysis with an oscilloscope.
5. AM reception tuned loop aerial.
6. How good is your eye?
7. How electromagnetic signal strength alters with distance.

Each of the activities varies in the time required, from about 45 minutes if equipment is ready to use, with students in groups of 3–4, to two or three times that.

Starting with the familiar

The intention is to use everyday examples to show some of the concepts of electromagnetic radiation that astronomers utilise to gain information about the universe. The strength of the linkage between these common examples and astronomy will depend on the particular objectives you may have in this area. While the concepts are not difficult, their practical realisation in astronomy can be complex and beyond the level of understanding required at this level.

An additional aspect is that activities are designed as much as possible to use simple, easily obtained and often cheap materials, so they could be carried out by students as individual or group projects.

As your time is limited, the teacher guide for each activity attempts to provide essential information. The 'extensions' section suggests topics for student project work, or for alternative group activities. References are given as URLs, mostly to Wikipedia as they are likely to remain available, to be updated, with diagrams often under the Wikimedia Commons licence so may be freely used.

Assessment

Assessment examples have not been included.

Radio telescopes

This resource is part of the **Square Kilometre Array (SKA) Project**, the largest international science project so far attempted. It would consist of an extensive array of radio telescopes providing a total collecting area of about one square kilometre, hence the project name. Australia has been short-listed as a location and it would also involve New Zealand to give a 5,500 km baseline—the longer the baseline the higher the resolution. The sensitivity and resolution of this array would enable it to see further into the universe, almost as far back in time as when it was formed.

From an educational perspective, the SKA project provides a context for several curriculum areas at different levels. It may also be where some of your students could work in the future.

For details of the whole SKA project see:
http://www.skatelescope.org/

For the Australian and NZ part of it:
http://www.ska.gov.au/Pages/default.aspx

For the NZ part of the project see:
http://www.ska.ac.nz/news

For an overview:
http://en.wikipedia.org/wiki/Square_Kilometre_Array

Teacher Guide to Activity One

CD Spectrometer and Measuring Wavelengths

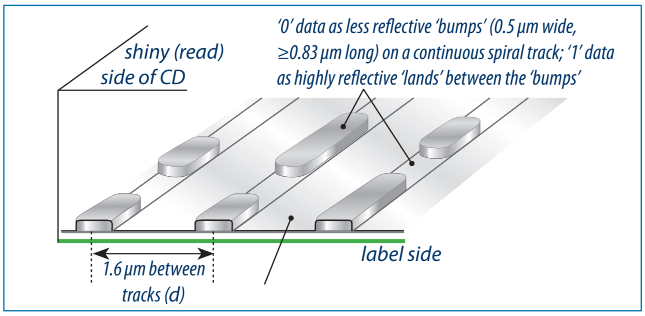
There are two "big ideas" here. The first is how reflections of light rays, which arrive in phase at the surface, and constructive interference can lead to reinforcement of particular wavelengths at particular angles of reflection. This is the opposite of radio telescope interferometry, where the telescope dishes receive the signals with phase differences between them due to the extra path length travelled by the signal in reaching the more distant dish. The extra path translates to phase difference. For example, if the extra path was half a wavelength then the phase difference will be π radians.

The second big idea is that the light from a source can be separated into its constituent frequencies which can then help identify the substance emitting those frequencies. This exercise builds on spectroscopy activities in this series at the lower curriculum levels. It takes those activities and extends them to making measurements of extremely small wavelengths.

In this activity students measure the reflection angle for different colours (wavelengths) of the incident light. The difficulty is to ensure the light arrived in phase at the different parts of the CD, and to then measure the angle. Knowing that CDs follow strict design protocols, so that the radius is always 60 mm and the track spacing is fixed at 1.6 µm, enables the student to measure the angle indirectly by measuring one distance.

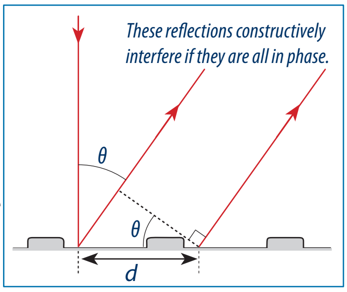
Background information

A CD spectrometer is only possible because the spacing of the tracks is a constant distance which is small enough for adjacent reflection paths that are in phase with each other to result in reinforcement. Ordinary CDs are made in a process that lays down tracks that are 1.6 µm apart. This is close enough that light rays reflecting in phase from adjacent track grooves can interfere constructively at particular wavelengths. The angle this occurs at depends on the wavelength of the light being reinforced. The diagram shows a simplified example. Note: as it is only reflection angles that are of interest, the incident light is irrelevant except for supplying light rays for reflection.

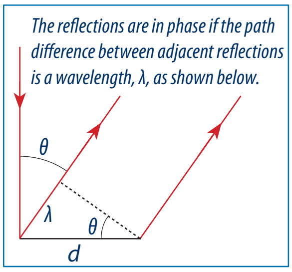


On a practical note, it is difficult to get a light source to shine on the centre of the CD when the observer's head is in the way. This can be overcome by using a headlight torch beam. In trialling this investigation a bright white light LED torch was used successfully. Cool white LEDs will have a different spectrum to an ordinary incandescent bulb, and is worth trying.

The student shines a light onto a CD surface, so that the central hole is illuminated. As the disc is moved away, the student will see concentric rings of colour.



If they measure the distance L from their eye to the disc surface, when the coloured ring is at the outer edge of the CD disc, they can use trigonometry to find the angle θ that results in constructive interference. They can then calculate wavelength λ, as they know the track separation, d, is 1.6 µm (1.6×10^{-6} m).



The radius of a normal CD is 60 mm, and the central spindle hole is 15 mm diameter.

The calculation is:
$\theta = \tan^{-1}(R/L)$ and $\lambda = d \sin \theta$

Equipment

1. A white LED torch or similar compact bright light source.
2. An old CD.
3. A metre rule or tape measure.

References

http://en.wikipedia.org/wiki/Diffraction

http://en.wikipedia.org/wiki/Compact_Disc

http://en.wikipedia.org/wiki/Astronomical_spectroscopy

Outcomes

- Increased student awareness of the effect path differences have on phase and the resultant existence of different constructive interference angles for different wavelengths.
- Improved understanding of diffraction and interference and how wave behaviour can be used to make measurements.

Extensions

Students could find the track separation (pitch) on a DVD using a similar technique with a laser of known wavelength.

DVDs are the same dimensions as a CD but the track separation is only 0.74 µm (i.e. 740 nm). Using a He-Ne laser with a wavelength of 633 nm would result in the reflection angle for constructive interference being too large (at nearly 59°) for the ring of light in the previous method to be used. A green or blue laser would make it possible, but these lasers are not readily available cheaply, so a much better method would be to remove the aluminium shiny reflecting surface from the disc and use the now transparent disc as a transmission diffraction grating replica. To remove the shiny coating (label side) pull it off with masking tape, starting from the outer edge.

CD Spectrometer and Measuring Wavelengths

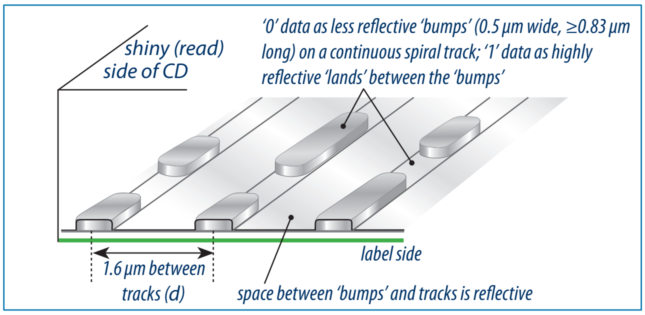
The purpose of this activity is for you to become familiar with a technique of using a CD as a diffraction grating to measure the wavelength of light using constructive interference of reflected rays.

You will need an old CD disc, a compact light source (such as a bright white LED torch) and a ruler.

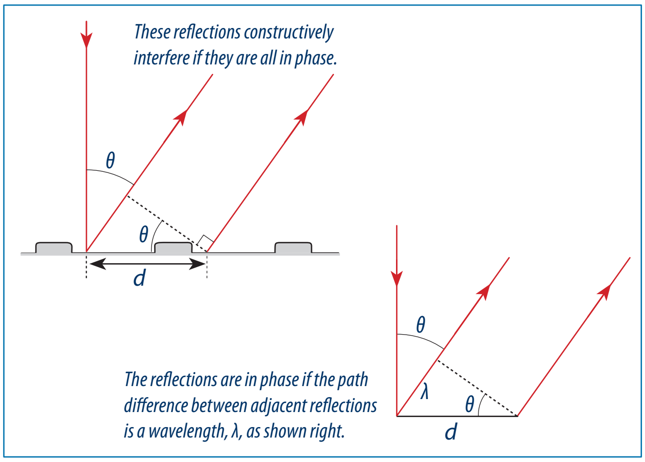
How this technique works

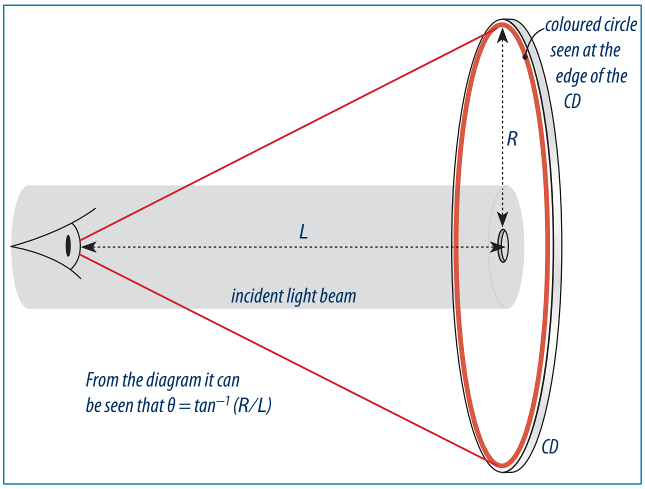
A CD has a single spiral track with each turn spaced 1.6 µm apart. The tracks have raised 'bumps' as seen from the shiny (read) side, but as 'pits' from the label side. The bumps are less reflective from their shape, and from being above the focus of the laser used to read it, and encode the '0' of a digital code. The 'bumps' are of different lengths. The space between the 'bumps' (where it is called a 'land') is highly reflective and encodes the digital '1' code. These are also of different lengths.

This activity utilises the reflection from the shiny gap between the tracks.



When light shining on a CD surface reflects at a particular angle, θ, the adjacent rays, which arrived in phase before reflection, will still be in phase after the reflection. This occurs when λ is the same size as the angle given by $d\sin\theta = \lambda$. The derivation of this equation is shown below.





Procedure

1. Shine a white light onto a CD surface and ensure that the light beam is centred on the spindle hole in the centre of the CD. (Using a head torch is an easy way to achieve this.) Holding the CD with the light coming from over your shoulder, or by using a head torch, gradually move the CD away from you until a coloured ring appears. The first ring to appear will be red and the last ring to appear as the CD continues to be moved further away will be blue/violet.
2. At each chosen colour, adjust the position of the CD surface from your eye so that the coloured ring is around the outside edge of the CD and carefully measure the distance from your eye to the disc surface (L). Record your results on the table below and complete the calculation to find the wavelength of the light.
3. Complete the table for at least 3 colours.

Note: the track separation (d) = 1.6×10^{-6} m, and the radius of a normal full-size CD is 60 mm.

Colour	Distance L (m)	Angle θ: $\theta = \tan^{-1}(0.06/L)$	Wavelength $\lambda = d\sin\theta$ (m)

Questions

1. Compare your answers with known wavelengths and comment on any significant differences.

2. Describe how you could use a He-Ne laser ($\lambda = 633$ nm) to confirm that the track pitch is 1.6 microns.

Extension

Use the same technique to find the track spacing on a DVD.

Shine a laser of known wavelength (He-Ne red laser pointers have a wavelength of 633 nm). You can use reflection interference to do this or, by removing the reflective layer on the DVD, you can shine the laser through, as happens in a standard diffraction grating.

Make and Use a Directional Aerial

This activity examines the design principles behind a yagi directional aerial and its application to a simple low power 433 MHz transmitter/receiver link. Enhancing weak signals is a challenge for all branches of astronomy.

Yagi aerials were invented in 1926. The essential principle is that the driven element is a half wavelength dipole with each arm being ¼λ. The reflector is of similar length and causes reflection (or re-emission) of the signal so that it is in phase with the signal arriving at the driven element, constructively interfering with the signal, creating a stronger signal for the receiver to process. The shorter director elements provide further enhancement of the original signal, but they resonate at slightly higher frequencies, increasing the further the director element is from the driven element.

The design program used in this activity will work for many different possible diameters of conductor used for the various yagi elements. It is suggested that the simple design mentioned in Activity Three Level 7 is used and that the boom is made from 20–30 mm diameter dowel (about broom handle size).

All of the elements are connected to the boom using 'chocolate block' connectors. The wooden boom insulates the elements from each other. All of the elements except the driven element are each one piece. The driven element is in two pieces (it is a dipole) with a combined length as given on the diagram. The centre wire of the coax is connected to one piece and the shield to the other piece.

The length of the boom determines the gain of the aerial. The length and spacing of the reflector, driven element and the directors depends on the frequency being detected.

It is suggested that groups design the yagi and build the transmitter and receiver circuits. Suitable wire is obtained from wire coat hangers or from high tensile fencing wire. A good wire cutter of the bolt cutter type is recommended, and that pieces of polystyrene foam, corks, or pen caps are taped on the ends of the cut wire elements to reduce the possibility of injury from the sharp ends.

The transmitter and receiver units tested in the development of this exercise worked well and were easy to set up on a breadboard. The circuits used are extremely simple. More permanent circuits could be built using printed circuit boards or stripboard (e.g. Veroboard®). A simple permanent version of the breadboard circuit could be built on a printed circuit board that mimics the hole spacing and connections of a breadboard, making transferring the breadboard circuit to a PCB a very simple and quick exercise if a permanent version of the circuit is desired.

Rationale

The 'big idea' here is enhancing detection of weak signals. It is related to astronomy and emphasises the fact that things do not have to be visible to know they are there.

Radiation detected from a point in space is an indication of a presence that may not be detectable optically. In this investigation a hidden transmitter will be located by using a directional aerial to fix the transmitter location.

The other big idea in this activity is that electromagnetic signals are a form of energy. All aerials capture this energy and the information carried by it, so wavelength is the critical consideration in aerial design.

Directional receiving aerials concentrate the signal and are more discriminatory regarding the signals they receive, and the direction they come from, than simple whip aerials. When yagi aerials are used with the transmitter they greatly increase the reception distance along the direction of the yagi boom. Much of this is well beyond Level 8 and so only the most fundamental principles of operation are considered.

The direction finding exercise is to emphasise the role directional aerials play in identifying the position of a source of electromagnetic signal energy in an entertaining and educational manner. Source location, using more sophisticated direction finding techniques, is used in radio telescope arrays as well as in terrestrial applications.

This activity aims to go further into the design of a yagi aerial and for the students to build one and then use it to find a hidden transmitter emitting a signal modulated with an audio tone.

The aerial design emphasises the resonant aerial length and introduces the idea of the reflector element which is a common feature of yagi and other aerials used in VHF and UHF reception.

This activity uses the same design program used in Level 7 Activity Three and examines briefly the important aspects of the design. The full construction notes for the yagi are given there too.

The student-designed yagi is connected to a receiver unit and the signal is amplified or just measured on a meter.

Equipment

Per group of 3–4:

1. Computer with internet access (or use the design given here).
2. Lengths of wire 2–3 mm diameter (old wire coat hangers will suffice).
3. 400 mm length of wooden dowel about 20–30 mm thick.
4. Tools and hardware (eg staples or tape) for cutting wire and attaching it to the dowel.
5. Electrical "chocolate block" connectors to connect the wire elements of the yagi to the dowel.
6. Length of connecting wire coaxial cable.
7. 433 MHz transmitter and receiver modules on breadboards.

8. Flashing LED, 330 Ω resistor and link wires for modulation and 4.5V or 6.0V pack connected to the transmitter.

9. NPN general purpose transistor (eg BC547), 5V piezo buzzer, wire links and 4.5V or 6.0V battery pack connected to the receiver.

All the above electronics are available from most electronic component suppliers. The ones used here were sourced from *Electroflash Resourcing.* It is important to use flashing LEDs with this circuit, as these contain a small integrated circuit that performs the flashing function. Ordinary LEDs would not provide any modulating effect on the data pin.

References

Yagi Design:
http://www.k7mem.150m.com/Electronic_Notebook/antennas/yagi_vhf.html

http://en.wikipedia.org/wiki/Yagi-Uda_antenna

An excellent resource is the "Radio Waves" demonstration apparatus and handbook, supplied to schools as a kit by the NZART Radioscience Education Trust:
http://www.nzart.org.nz/nzart/waves/radiowaves.html

Electroflash Resourcing: http://www.electroflash.co.nz/

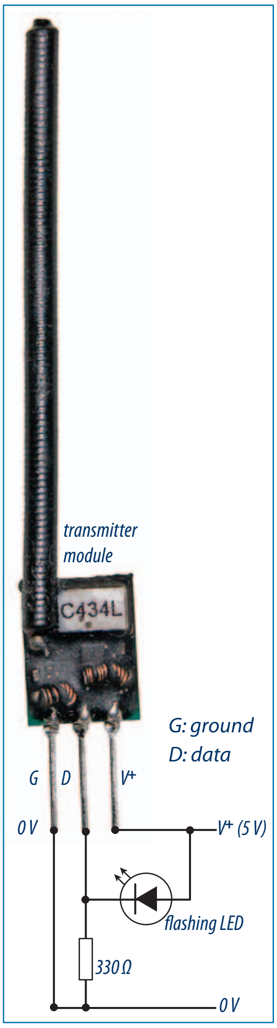
PICAXE resources: http://www.picaxe.com/

http://www.picaxe.orconhosting.ne.nz/

Outcomes

- Students should clearly observe the directional and enhanced signal effects of the yagi aerial.
- There should be a clear recognition that information can be loaded onto an electromagnetic signal through modulation at one end (transmitter) and that the information being carried can be extracted at the other end (receiver).

Background Information

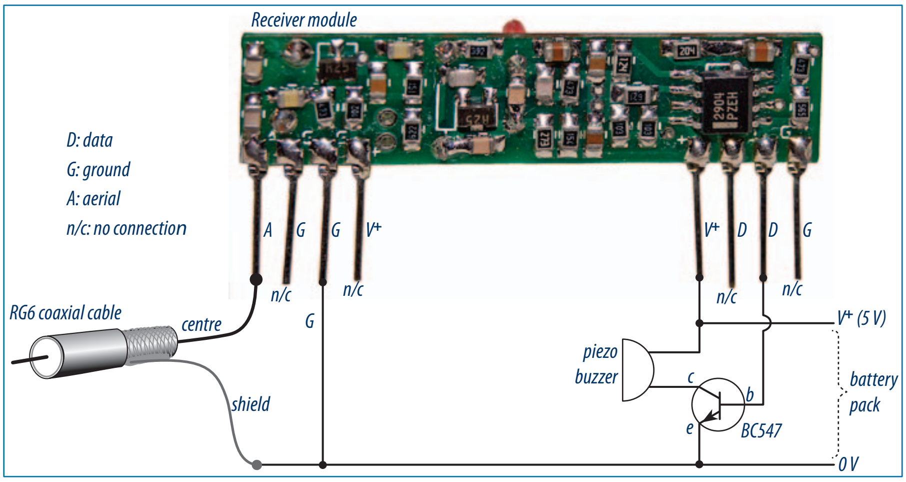


These transmitter and receiver units come in several different types of package and specification, and, although ostensibly digital data devices, they can transmit and receive analogue signals like speech or music, although the reproduction is certainly not hi-fi! Other units can be substituted for these and many are pin-compatible for connection, but this is not guaranteed, so a quick check of the specifications is recommended if other options are used.

The transmitter module shown left has a whip aerial. A small transmitter may be easily built and connected to a whip aerial made from a length of wire shortened by curling it into a helical open-wound spring to form a 'pigtail' aerial. *Hint:* winding the aerial wire around a pencil or similar works well. The length of the aerial for this band should be about 170 mm.

There are only two components added to the transmitter and two components added to the receiver circuit. More sophisticated circuits, with attendant increase in complexity, can be substituted if there is the need to take these ideas further.

These units are designed to work on 5V, but will work with 3–4 alkaline cells giving 4.5V or 6V. If using rechargeable cells the voltage must be >4.5V (e.g. four Ni-MH cells gives 4.8V).



The photos and circuit diagrams for the transmitter are shown above and for the receiver left:

Extensions

1. Fox Hunting:
A challenge could be undertaken between groups ('hounds') to see who could find the transmitter ('fox') first. An alternative is to use 2 'hounds' to get a fix on the location of the 'fox'. The hounds would now separate and get a fix on the direction from their position to the fox. A third student (who also does not know the position of the fox) is sent to locate

it at the intersection of the two directions from the hounds. The intersection of the two directions is more accurately found the greater the separation of the hounds. This leads to useful discussion on finding radio sources in space. The accuracy of the measurement of their position in space and distance from earth depends on the base separation of the terrestrial receivers. This is one benefit of *Very Long Base Line Interferometry (VLBI)*.

2. Investigate how the elements of a yagi affect its performance, by starting with just the dipole aerial on the boom, and then adding the reflector, trimming it, and adjusting the separation from the driven element. Adding directors could be done increasing the complexity of the investigation.

3. The flashing LED modulator could be replaced by the output from an MP3 player. This would require a more sophisticated amplifier, connected to a speaker instead of a buzzer at the receiver end, if music is to be transmitted and received.

4. Using a microcontroller to supply real data to the transmitter and to process the data from the receiver. A PICAXE microcontroller like the PICAXE 08M is ideal for this, and works well in this application when trialled for this activity.

To simplify the initial development of this activity, the transmitted data was provided by a PICAXE 08M microcontroller chip and the received data was processed by another 08M microcontroller, which re-sent the data to a computer screen for viewing. The advantage of this approach is that it is easy to progress step at a time, ensuring data is being transmitted to begin with, and that the received data is in fact the data that was being transmitted. The 433 MHz modules are very easy to connect, but not so easy to ensure that a good link is made between them, so the microcontroller approach has considerable merit. The 08M chips are programmed using a serial port on a PC computer or by using a USB port and a dedicated connection cable (AXE 027) which has a USB-to-serial converter built into it. It is recommended that teachers have some familiarity with programming these chips before offering this approach to their students. The PICAXE system was chosen as an option for this extension activity because:

- It is cheap.
- It is very simple to program.
- The resources available to the user are very extensive, well organised and instantly available at the click of a mouse button.
- Changing the operation being carried out is as simple as downloading a new program.
- The support literature for this system is vast and some of the better sites are listed in the references above.
- PICAXE suppliers in New Zealand are numerous.

Electroflash Resourcing have been heavily involved in the running of courses for teachers on the use of the PICAXE system and are very familiar with the needs of schools and can offer sound advice.

Make and Use a Directional Aerial

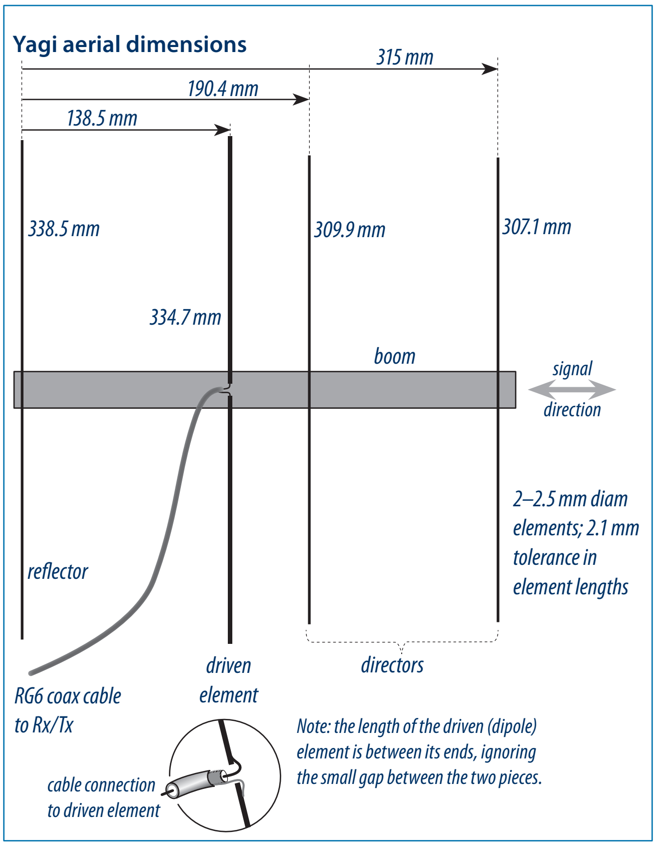
Signals from an omnidirectional source rapidly lose intensity (inverse square law). To receive the signal and locate the source direction requires an aerial which is efficient and directional. Yagi aerials are highly directional and efficient. The best reception from an omnidirectional signal source will be when the boom is pointed towards the signal source.

This activity takes you further into the design of a yagi aerial. It requires you to build one and then use it to find a hidden transmitter emitting a signal modulated with an audio tone at about 3 Hz.

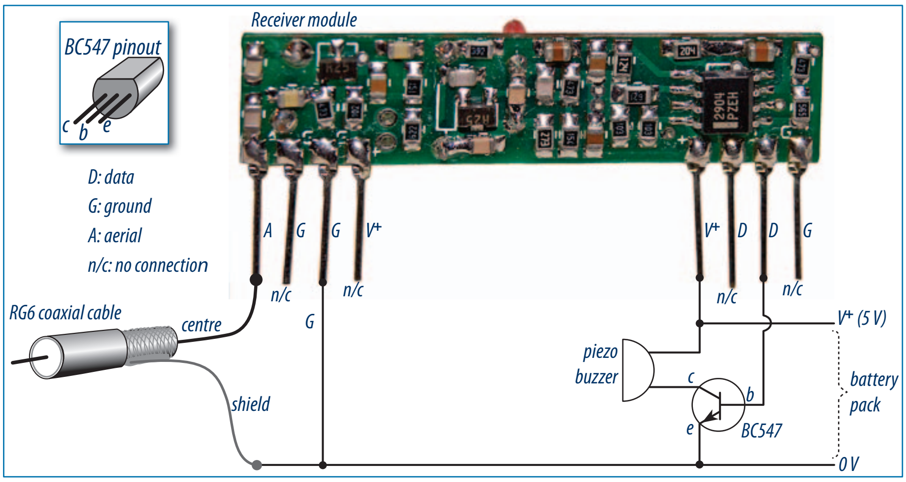
The aerial design emphasises the resonant aerial length and introduces the idea of the reflector element which is a common feature of yagi and other aerials used in VHF and UHF reception.

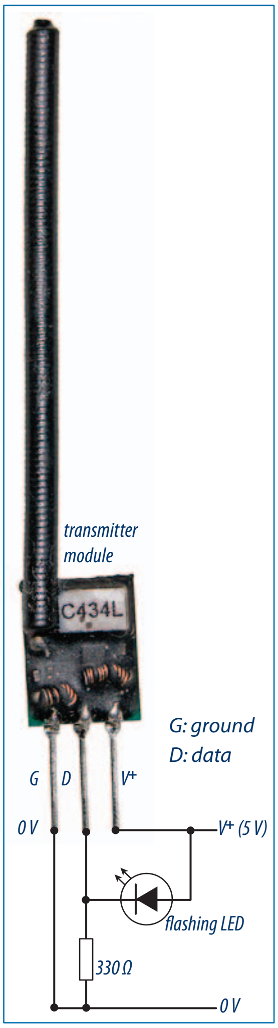
What to do

1. Design a Yagi aerial for the 433 MHz receiver module. Use the suggested URL or choose your own design. If a computer is not available, a suitable design is given below. The longer the boom (and the more elements used) the more directional it is, which also makes it better at receiving or sending signals.
2. Build the yagi aerial using components supplied.



3. Build the receiver (shown immediately below) and transmitter circuits (below) using the components supplied. It is important to ensure you have all the components in the circuit the right way around. Note that in the receiver circuit pictured there is a link to the data pin from the base (middle leg) of the transistor.

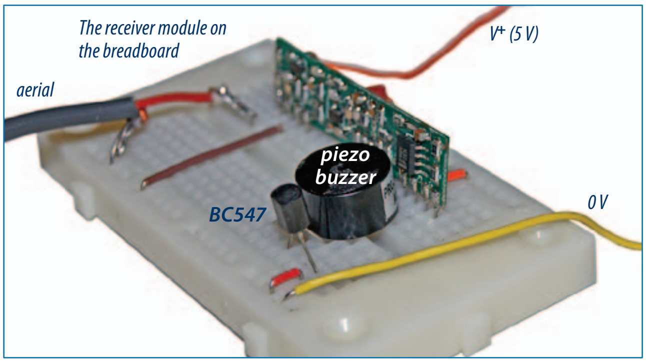


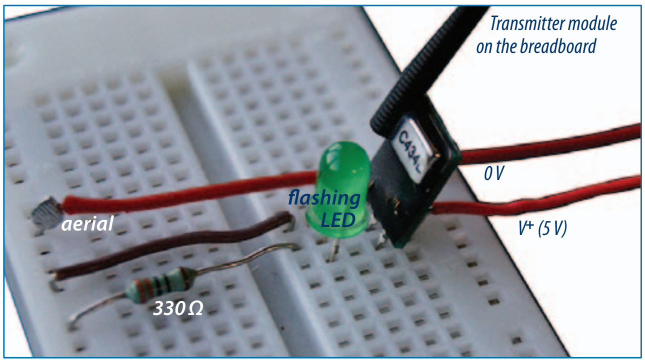


It is not visible under the piezo buzzer placed next to it in the circuit in the photographs on the next page.

4. Make a 'pigtail' aerial of about 17 cm for the receiver aerial (and another for the transmitter if it does not have one built in).
5. Set the units up close to each other and ensure that the receiver is detecting the signal from the transmitter. The transmitter signal is observed by watching the flashing LED. The received signal should be an alternating (modulated) tone coming from the piezo buzzer.
6. Investigate and record the maximum distance that a reliable link can be established between the transmitter and receiver. This is when the buzzer no longer changes tone. Record this distance.

7. Once the link between the transmitter and the receiver is well established and its maximum range has been observed, replace the original pigtail aerial on the receiver with the yagi aerial. Connect the driven element's coaxial cable centre wire to the aerial connection and the shielding wire from the coaxial cable to the ground connection or the negative battery terminal for the receiver module.





8. Investigate and record the maximum distance that a reliable link can now be maintained between the transmitter and receiver. It should be more than for the pigtail aerial. Observe how the reception changes when the boom is directed away from the source. When the signal is strongest the modulated tone should be at its clearest.

9. Well within the maximum range of the link, get one of the group to hide the transmitter 'fox' and see how long it takes another member of the group to locate the 'fox' using the receiver connected to the yagi aerial as the 'hound'. Describe how the 'fox' was most efficiently located.

Young's Double Slit at Radio Frequencies

Radio interferometry deals with receiving signals from a distant source at several receiving stations. From the separation of the stations, and the timing and phase differences in the received signals, information can be deduced about the source, including its size and position. This approach is totally dependent on the received radio signals exhibiting the wave-like behaviour of interference.

In Young's Double Slit experiment two point-sources are created by diffraction of a coherent light source through very narrow closely-separated slits. The result is an interference pattern that can be seen and measured on a wall some distance away. The same effect would happen if the slits had been replaced with actual point-sources, and in fact a more complicated pattern would be formed if a whole collection of point sources were used. Radio interferometry does this in reverse. It stands to reason that if the interference pattern is known, then by reversal of the paths, the source(s) can be identified. This is the principle behind holography and radio interferometry.

Rationale

In Young's Double Slit experiment a light source and diffraction through two narrow apertures were used to create the interference pattern. In this investigation the apertures are replaced by actual point-sources at radio frequencies in the form of PRS 'walkie-talkie' radio whip aerials.

This investigation confirms that radio waves have similar wave interference behaviour to visible electromagnetic radiation. While it is not practically feasible it would, in theory, be possible to have an array of PRS units acting as sources and a detector unit at a considerable distance away locating where maximum constructive interference occurred. (This would, of course, model the opposite of the SKA, where the receiving dishes are the equivalent of the sources mentioned above).

Equipment

For each group carrying out the investigation:

1. Three PRS walkie-talkies. (PRS: Personal Radio Service, UHF CB These have 40 channels utilising frequencies from 476.425 MHz to 477.400 MHz; $\lambda \approx 0.63$ m.
2. A tape measure and a metre ruler.

References

http://en.wikipedia.org/wiki/Wavelength

http://en.wikipedia.org/wiki/Diffraction

Outcomes

- Observation and confirmation of Young's Double Slit (or two-point) interference at radio wavelengths.
- Confirmation that radio signals exhibit the same wave interference behaviour as visible light.

Background information

A PRS (Personal Radio Service, UHF CB) walkie-talkie has 40 channels utilising frequencies from 476.425 MHz to 477.400 MHz ($\lambda \approx 0.63$ m).

When using a PRS walkie-talkie for the radio signal do **not** use these channels:

- 1–8 (these are repeater channels and you do not need to take up repeater space, with channel 5 for emergency use only).
- 22, 23 (these are telemetry channels only).
- 35 (this is for emergency use only).

It is advisable to first listen on the channel selected for use to find if there is anyone already using it.

Extensions

1. Applications of diffraction of light, e.g. the many applications of diffraction gratings; diffraction-limit of lens resolution; lens coatings which utilise interference for effectiveness; etc.
2. Diffraction of radio waves around objects, see:
   http://en.wikipedia.org/wiki/Knife-Edge_diffraction
   and:
   http://www.tpub.com/content/neets/14182/css/14182_73.htm

Young's Double Slit at Radio Frequencies

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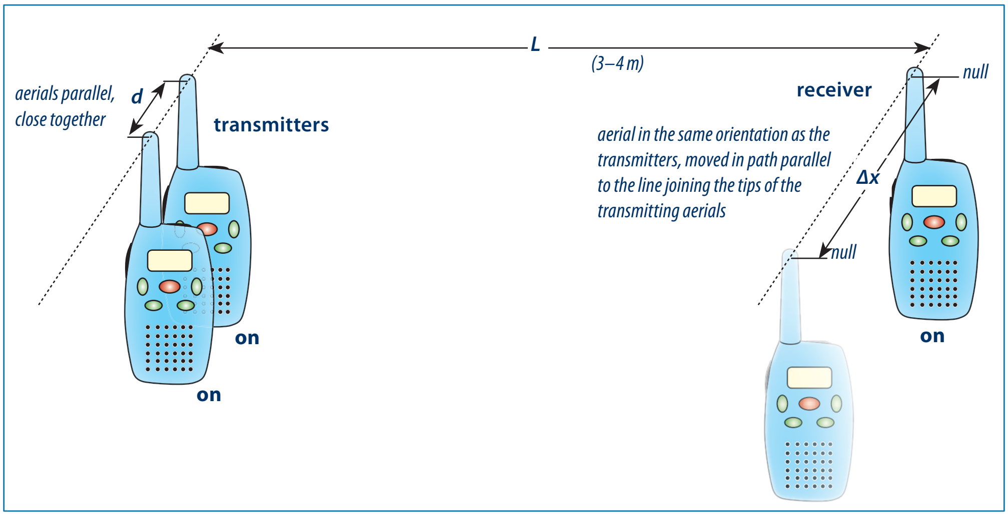
Procedure

1. Set all 3 walkie-talkie handsets to the same channel* and then place one (in the receive mode) at 3–4 m away (*do **not** use channels 1–8, 22, 23, or 35).
2. Hold the two walkie-talkie handsets (in transmit mode) so that their antennae are only a few centimetres apart.



3. Move the receiver set from side to side along a path parallel to the line joining the tips of the two transmitter antennae.
4. An observer should be able to detect places where the receiver detects weak signals (nulls). Measure the separation (Δx) between these nulls by measuring the distance between the aerial positions for each null.
5. Measure the separation (d) of the transmitting antennae and the distance (L) to the line the receiver antenna is moved along.
6. Calculate the wavelength (λ) of the radio carrier wave from the formula: $\lambda = \Delta x d / L$
7. Record your value for the wavelength, λ.

Results

Δx = ____________________

d = ____________________

L = ____________________

Calculated λ: ____________________

Your measurement of λ: ____________________

Spectral Analysis with an Oscilloscope

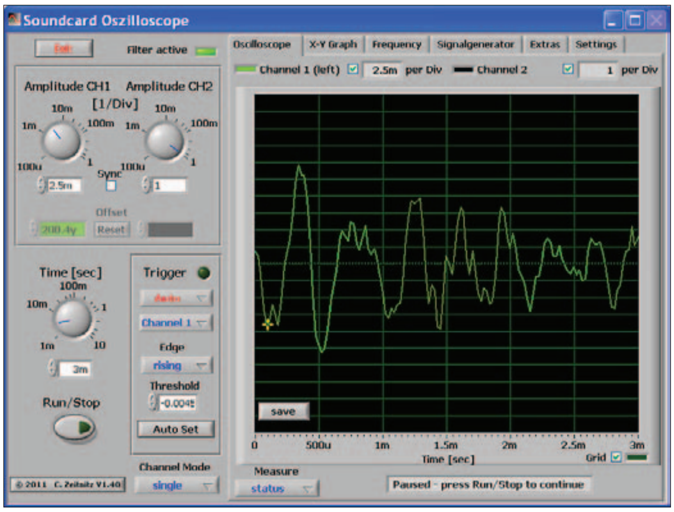
The first Level Eight activity used a spectrometer made from a piece of CD to examine the spectrum of light. The big idea here is to extend this concept of spectrum analysis to methods of spectrum analysis of radio signals. To do this the signal is captured and computers are now used to break down the signal into its constituent frequencies.

Schools may not have the hardware for an analysis of high frequency radio signals like UHF. However, a cheap and readily available alternative is to use a software oscilloscope using the sound card in a computer. We cannot use a computer sound card for high frequency signals, but we can model the analysis of a radio signal using a lower frequency signal derived from a microphone input to the sound card.

An internet search will yield many possible oscilloscopes that would be suitable for this exercise. The one used here (Windows only) was obtained from: http://www.zeitnitz.de/Christian/scope_en

This is better than many shareware oscilloscopes, and has a useful frequency screen showing frequencies as well, which is why it is suitable for this activity.

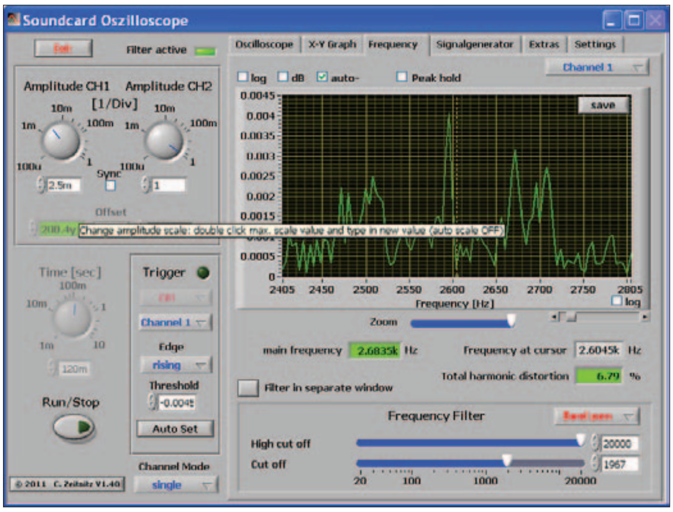
The screen capture below shows the raw signal captured by the computer sound card and held by pressing the Run/Stop button. The Time [sec] button is rotated to get the complete signal for processing.



By switching windows, the user can now see the amplitude and frequencies of the signal that make up the original waveform captured on the previous screen.

Below is a screen capture of the computer oscilloscope with the window changed to show frequency.

For the signal shown in the first screen capture we can now see that the main frequency is at 2.6035 kHz. Other frequencies that are part of the signal are shown by peaks and may be measured by pulling the yellow-dotted marker across to the peak in question. The frequency value is then shown on the screen.



Students could try to produce a useful signal by singing or whistling a note into the microphone. The microphone will require a 3.5 mm plug for the sound card microphone input socket. The input has to be set to 'Microphone' in the sound card menu. Some adjustment of the time-base and sensitivity dials are needed, but these can be adjusted after signal capture.

The program used here is typical of shareware/freeware PC oscilloscopes. These have their limitations, but provide reasonable features for the level of analysis considered in this activity. The real limitation here is the frequency limit of the sound card which, not surprisingly, stops at the ultrasonic frequency of 20 kHz. Analysis of signals can therefore only be done on signals below this frequency, well below most radio frequencies.

Materials and equipment

1. A PC loaded with the required *Soundcard Oscilloscope* program.
2. Microphone connected to this computer.
3. Sources of suitable signal, e.g. voice, transistor radio or MP3 player, tuning fork, etc.

References

http://www.zeitnitz.de/Christian/scope_en

http://www.sciencetronics.com/geocities/electronics/projects/soundcard_osci.html

Fourier Transformations and Fast Fourier Transformation algorithms are beyond the mathematical capability and knowledge of students at level 8. FFTs were only implemented in the 1960s. The following link is for those who have a particular interest: http://mathworld.wolfram.com/FastFourierTransform.html

Outcomes

Having used software to analyse sound signals, students will be aware in principle of the use of software to analyse the spectrum of any signals.

Extensions

Although not related to the SKA astronomical context, this would be an ideal opportunity to study harmonics and resonant frequencies using this software. A student (with a good singing voice!) could sing a note and the harmonics that are present could be easily observed. Different musical instruments, each playing the same note could be recorded and their harmonics analysed.

Student Activity Four

Spectral Analysis with an Oscilloscope

This activity models the concept of using a computer to analyse the spectrum of a radio signal by analysing a sound signal.

Procedure

You will need a computer with a microphone and oscilloscope software able to show a spectrum analysis of a sound signal.

Ensure the microphone is connected and that the sound card is recording the microphone input as shown by the change in the oscilloscope trace. Some adjustment will be needed to the time-base and sensitivity dials to ensure the signal being considered is visible in the screen window.

Get a source of sound to create a signal showing on the screen. Capture the signal – usually by pressing the stop button.

1. Observe the signal and measure the period (*T*) of the signal if it is a repeating signal. Convert this to frequency (*f*): $f = 1/T$

   Frequency of Signal: .... Hz

   Now switch screens to the frequency screen. On some sound card oscilloscopes it is an FFT button.

2. Observe and measure the strongest frequencies that make up the original signal. These will be the ones with the highest peaks on the frequency screen. Measure the strongest frequency.

   Strongest frequency: .... Hz

3. How does the measured frequency of the signal compare to the strongest of the frequencies it is made from?

4. What is the effect on the signal of the other frequencies?

5. The principle of superposition states that wave amplitudes add together when the waves combine. What would the shape of the signal be that was made up of all the frequencies and amplitudes indicated on the frequency display screen?

6. How could you use the oscilloscope to check that a signal was a "pure" note of only one frequency?

7. What would be the shape of a note with only one frequency? (If unsure of this get someone to sing or whistle a pure note and observe the waveform).

8. Complete the following statement that forms the basis of Fourier analysis:

   Any repeating signal can be constructed from separate signals that are all .... curves.

Tuned Loop Aerial

The big idea here is that in the process of detecting a signal, the detecting aerial also acts as a transmitter for the signal, and can intensify it by using resonance.

This is very similar to the mechanical case of pushing on a child's swing with a small push in phase with the motion of the swing. In that example the amplitude of the swing builds up to a large value, but only when the push is at the resonant frequency of the swing. In the case of the tuned loop at resonant frequencies the current flowing in the coil has increased greatly and will induce currents in other coils nearby.

The other big idea in this activity is that a loop or coil is an inductor and responds to the magnetic field component of the radio signal rather than the electric field component as in the other aerials that have been considered. This is also a powerful illustration of a noise reduction technique.

Materials and equipment

This will depend on the aerial chosen and the method of construction.

1. Tuning capacitor.
2. Wire, 'chocolate block' connectors and suitable screwdriver (see coil types below for details).
3. Wire cutter/stripper pliers.
4. Soldering iron (if not using 'chocolate block' connectors).
5. Insulation tape.
6. Small AM radio.

Making the coils

To calculate the inductance of a wire loop use either Wheeler's Formula or Nagaoka's Formula. There are several sites on the internet (e.g. http://www.qsl.net/in3otd/indcalc.html) that will do the calculations for you. Nagaoka's formula gives an inductance of about 500 µH if the coil has 10 turns and a radius of about 20 cm. The actual value is not critical as resonance is achieved by adjusting the capacitance. However, if the capacitor cannot get the adjustment right then the inductance will need to be adjusted and this is easily done by changing the number of turns on the coil if either of the first two methods have been used.

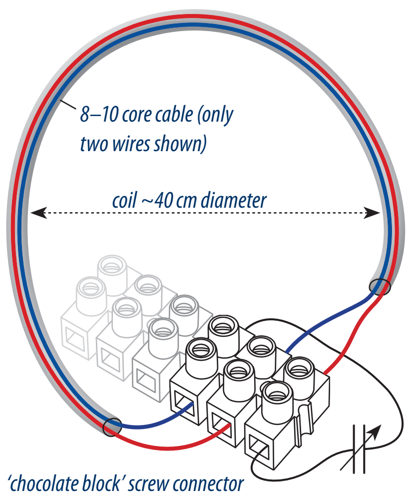
COIL 1:

This coil is most easily made using a length of 8- or 10-core cable, with each wire having a different colour insulation. The length of cable needed obviously depends on the radius chosen for the coil and the number of turns in the loop. Increasing the number of turns means the coil can have a smaller radius.

To make the coil:

Assuming the wires can be identified by colour, e.g. red, white, purple, blue, green, orange, etc:

- Strip back the sheathing of the cable a few centimetres from each end.
- Bare the ends of each core wire and do this at both ends of the cable.
- Connect one end wire, e.g. red, into one side terminal of a 'chocolate block' connector (these are chunky connectors used by domestic and automotive electricians).



'chocolate block' screw connector with only two strands of wire and the tuning capacitor to show how the wire is connected to form a coil, continue connecting the loops in the same way for the required number of turns (drawing not to scale)

- Connect the next wire along, say blue, to the same connection as the existing red wire connection. Note that the other end of the red wire will eventually be connected to the tuning capacitor.
- Connect the other end of the wire (blue in this example) to the next chocolate block connector. Repeat this connection process so that you end up with a series connection going from one wire to the next. As each wire is in a loop the end result is a 10 turn coil. The unused wires from each end are now connected to the terminals on the tuning capacitor.

The tuned aerial is now complete, and has the advantage that the number of turns is easily increased by using the wires of another length of cable to continue the series connections until the inductance of the loop allows the capacitor to tune up and down from about the middle of the band.

COIL 2:

An alternative coil is to use computer ribbon cable of the right length and with a computer header pin strip connector on each end.

- Use a strip of header pins connected onto one header strip which connects to the header strip on the other end, but with the connections stepped over one place.
- This results in the two unused ends to be connected to the tuning capacitor as before.
- As computer cable comes with a lot more than 10 conductors a wider range of inductance is possible by connecting in more loops (i.e. by having the two header strips overlapping each other more fully and allowing more pin connections).

COIL 3

Long lengths of single core wire could be used, especially if a trial had been done beforehand to establish the optimum length. It would then be very easy to make a kit containing the right length of wire, a tuning capacitor with two short wires pre-soldered to its terminals and connected to a double chocolate block to connect the ends of the coil once the students had wound them.

Hint: Once the coils have been made, the loops can be held together by taping them together at regular intervals.

Small tuning capacitors are getting harder to come by but are currently available with a range of about 60–150 pF from retail electronics suppliers. Larger air core plate capacitors can be salvaged from old radio equipment and have higher capacitance values.

The loops in method 1 or 2 can be made self supporting. Lightweight LDPE irrigation pipe of about 13–20 mm diameter, with a joiner connecting the ends, could be used. The two wires for the tuning capacitor could come out through a small drilled hole in the pipe, and the capacitor attached (tape or glue) to the outside of the coil. To fit into the smaller pipe the connections would need to be soldered and insulated.

Outcomes

- Increased understanding of the reception of a signal and the electromagnetic induction of currents in a loop or coil.
- Observation of the reduction of noise interference with the desired signal and the increased reception ability afforded by the tuned loop.
- Observation of a practical application of inductor- capacitor resonance.

Extensions

Students could make crystal radios or a simple capacitor inductor oscillator and observe its behaviour on an oscilloscope when it is fed a signal (eg the test square wave signal provided on many oscilloscopes. The components should be chosen to ensure the resonant frequency was several times higher than the square wave frequency. This would result in the oscillatory wave form being observed at edges of the rise and fall of the square wave (ringing). The effect of inductors and capacitors forming a filter in loudspeaker systems could also be observed or investigated.

Tuned Loop Aerial

In this activity the tuned loop is a coil of wire with quite a large diameter and several turns of wire form a coil of inductance L. The ends of the wire are connected to a small tuning capacitor of capacitance C, so that the loop (which ***is*** an inductor) and the capacitor form a resonant circuit with frequency f given by:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

This means that if the radio signal is of the right frequency then the loop will amplify the signal at that frequency. The tuned loop responds to the changing magnetic component of the chosen radio signal and this causes a changing current to flow in the loop at the same frequency as the radio signal.

The energy carried by the current is stored in the electric field of the tuned loop's capacitor and the magnetic field of the coil inductor of the tuned loop. The stored energy increases with each full cycle of the radio signal until the currents in the coil are losing energy (mainly as heat in the coil) at the same rate as the energy is arriving from the radio signal.

If this tuned loop is placed near a domestic AM radio then there is ***magnetic flux linkage*** with the ferrite core coil aerial inside the radio, so the AM radio receiver will have a stronger signal than it would have had without the external loop. This means weak stations can be heard with much greater signal strength. There is an added bonus that as most AM frequency interference is electric, so using the *magnetic* component of the signal amplifies the radio signal without amplifying the interference as well. This gives a much clearer reception with relatively little noise.

If the radio is able to work with FM it will most likely also have a small telescopic monopole aerial working on the electric part of the signal. This is because the ferrite core is not capable of working with frequencies higher than a few MHz, whereas the FM band is around 100 MHz.

What to do

Build a tuned loop to demonstrate response to the magnetic field of an electromagnetic signal, and to illustrate reduction in electrically generated noise.

1. Make a coil with the materials provided and connect it to the tuning capacitor to form a simple series circuit.
2. Turn on the AM radio and tune to a distant station around the middle of the AM band so that reception is faint and 'crackly'.
3. Place the radio inside the loop and slowly adjust the tuning capacitor until the reception improves. The radio may need to be oriented in the coil to improve reception, which happens when the internal ferrite core aerial is along the axis through the middle of the loop.

   Carefully note the improved reception and the reduction in 'static.'
4. Why is reception improved most if the ferrite aerial of the radio receiver is along the axis of the coil? Explain your answer in terms of magnetic fields and electromagnetic induction. Include a diagram.
5. Most radio 'noise' is electrical interference caused by the myriad of electrical devices used in our modern environment. Explain why the tuned loop helps reduce the interference from 'noise' caused by electrical sources.
6. The capacitance of the tuning capacitor you have used is about 50–150 pF.

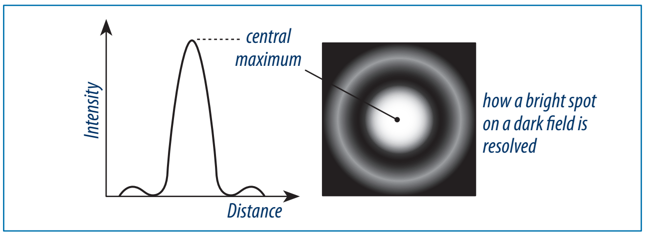
   Calculate the size of the capacitance that would be needed with a 100 μH loop to resonate at the frequency of 675 kHz.
7. What capacitance would be needed with the coil used in the previous question if the tuning coil antenna was intended to work with an FM station operating at 92 MHz?
8. Explain, providing at least two reasons, why the tuned loop aerial is suitable for enhancing reception of AM stations (~500 kHz–1600 kHz), but not FM stations (~88 MHz–108 MHz).

How Good is Your Eye?

The ability to distinguish between objects is called resolution. The better the resolution the smaller the angular separation of things can be and still be detected as separate objects.

When waves (including electromagnetic waves) pass through an aperture the wave is diffracted and spreads out over a wider region.

A single point-source of light produces a diffraction pattern like the one shown here:



The diffraction pattern illustrated above can be seen by shining light through a small aperture.

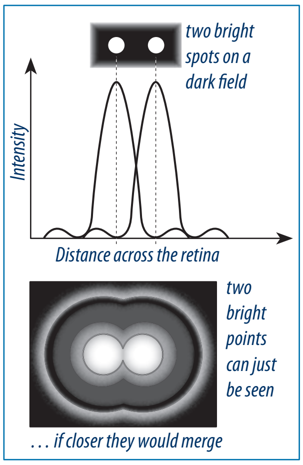
Two point-sources are well resolved (i.e. easily distinguished from each other) if the central maximum intensities from each are far apart. The minimum is when the first order diffraction node from one overlaps the central maximum of the other. This is called the Rayleigh Criterion and leads to the following rule:

$$\sin\theta = 1.22\lambda/D$$

where θ is the angular resolution in radians. This is very small and so $\sin\theta = \theta$. The angular resolution is often expressed as just λ/D:

Angular resolution $R = \lambda/D$

D is the effective aperture. In a direct observation optical telescope and eye system, D is the aperture of the pupil of the eye. For a radio telescope it is the diameter of the telescope dish.



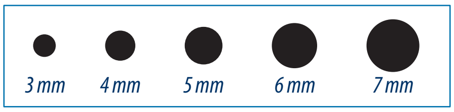
Rationale

When looking through a telescope (or any optical instrument) the eye becomes part of the optical system. Objects obviously can not be seen if the eye is unable to resolve them.

Radio telescopes are arranged to utilise the Rayleigh Criterion.

With a telescope-eye system, one limiting factor is diffraction, determined by the aperture of the eyepiece or of the pupil of the eye, whichever is smaller. The size of the pupil of the eye changes with light intensity and is also affected by age. The eye of an adolescent may have a maximum pupil diameter of 7 mm, whereas a person their 60s may have a maximum of 4 mm. There are obviously individual differences.

Your students are likely to have difficulty measuring the diameter of their pupil. Any method is likely to reduce the light intensity, causing the iris to immediately open up to compensate. Accuracy is not critical for this aspect, so a having a strip of paper with circles of known diameter held below the eye to use to match the pupil diameter to one of the circles is sufficient, e.g.



Equipment

Per group of 3–4:

1. A red laser pointer.
2. A microscope slide coated with soot or a thin layer of black spray-paint.
3. A single-edge razor blade and a ruler.
4. Something to (very carefully!) measure the pupil of the eye.

A darkened room is required.

References

http://en.wikipedia.org/wiki/Visual_acuity

http://webvision.med.utah.edu/book/part-viii-gabac-receptors/visual-acuity/

http://en.wikipedia.org/wiki/Pupil

http://en.wikipedia.org/wiki/Airy_disk

http://www.cambridgeincolour.com/tutorials/cameras-vs-human-eye.htm

http://www.telescope-optics.net/eye.htm

http://clarkvision.com/imagedetail/eye-resolution.html

http://www.aiga.org/content.cfm/typography-and-the-aging-eye

Outcomes

Students should (1) be able to relate the pattern of diffraction of light through a slit to factors affecting the resolution of the eye, and (2) have an increased awareness of the relationship between aperture size and resolution, and why astronomical telescope dishes need to be so big.

Background information

See: http://webvision.med.utah.edu/book/part-viii-gabac-receptors/visual-acuity/

Extensions

The pupil of the eye in relation to the exit pupil of binoculars. See: www.cloudynights.com/documents/binoexit.pdf

How Good is Your Eye?

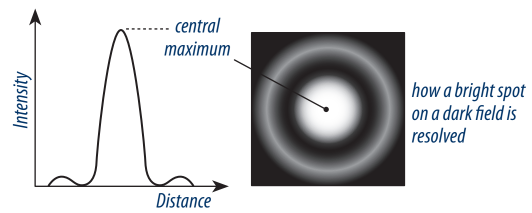
When using an astronomical, or any telescope, the eye becomes part of the optical system. The quality of the image data transmitted to the brain to interpret depends on the quality of the image formed by the telescope-eye system.

The ability to distinguish between objects is called resolution. The better the resolution the smaller the angular separation of things can be and still be detected as separate objects. The ability of the eye to resolve detail is referred to as acuity.

The density, size and distribution of the light sensitive cells of the retina are not even across the retina, so the acuity varies in different parts of the retina. Other factors, such as light levels, eye aberrations (e.g. astigmatism) and the ability of the eye to focus an image also affect the acuity.

When waves (including electromagnetic waves) pass through an aperture the wave is diffracted and spreads out over a wider region. With a telescope-eye system, the aperture (*D*) is either the exit pupil of the telescope eyepiece or the pupil of the eye. The exit pupil of the telescope eyepiece is known, the iris of the eye depends on the viewer's age as its maximum opening decreases with age, limiting the effective aperture.

A single point source of light produces a diffraction pattern like this, where there is a bright spot in the centre with concentric bright rings around it:



What to do

The diffraction pattern illustrated above can be seen by shining light through a small aperture.

To observe single slit diffraction:

1. Take a microscope slide or similar and coat with soot or a thin layer of black spray-paint.
2. Take a sharp blade (e.g. a single-edge razorblade) and make one cut across the coating, creating a slit the thickness of the sharp edge.
3. Shine a red laser pointer through the slit so it is visible on a white surface a couple of metres away.
4. You should be able to see the light spread out a little instead of just a bright red dot. This is single slit diffraction in action. Sketch the appearance of the light on the screen:

What is the angular resolution of your eye?

5. Measure the diameter of your pupil. This is the diameter, *D*, of the aperture. Describe how you measured it and what the problems were.

   D = ...

6. Now research the wavelength, λ, of blue light.

   λ = ...

   Angular resolution of your eye in radians: $R = \lambda/D$:

   R = ...

7. How big would the diameter of a radio telescope need to be have the same angular resolution as a human eye taken to be $\theta = 1.0 \times 10^{-5}$ radians? (The telescope diameter is like the aperture of an eye and the telescope is receiving wavelengths of 3 cm).

8. Depending on the age of the observer and the light intensity, the pupil diameter is likely to be within the range of 4–7 mm. Calculate the angular resolution, *R*, for the extremes of this range.

4 mm: ....

7 mm: ....

9. Telescope arrays (or astronomical interferometers) are set up using radio telescopes set up in 2*D* patterns. These arrays can set up to achieve angular resolutions *R* to the value of

$$R = \lambda/B$$

Where *B* is the distance between the radio telescopes. *B* is called the baseline.

What would you expect to happen to the resolution of the array in *Very Long Baseline Interferometry (VLBI)*, and why?

How Electromagnetic Signal Strength Alters with Distance

The big idea here is that the radiant energy from the radio source spreads out in all directions from an omnidirectional source like a monopole (¼λ whip) aerial. If the separation is doubled then the energy is spread over four times the area. The energy of a signal can be considered as proportional to the square of the signal voltage, so a simple investigation to examine this decrease in energy with distance can be carried out by detecting voltage across a diode at various separations from a source.

The inverse square law is that wave intensity from a point source diminishes in a predictable and geometric way. Although stars radiate huge amounts of energy their great distances from us means their signals are very faint. Activity Four for Level Four was a geometrical exercise; this investigation measures the signal level with increasing distance from a point source.

Equipment

Per group of 3–4:

1. Unmodified PRS walkie-talkie handset. (PRS: Personal Radio Service, UHF CB These have 40 channels utilising frequencies from 476.425 MHz to 477.400 MHz; λ ≈ 0.63 m. Do **not** use channels 1–8, 22, 23, or 35.)
2. Digital multimeter and leads.
3. Signal diode.
4. Metre ruler or measuring tape.

References

A good coverage of the concepts involved in signal attenuation and with appropriate mathematics:
http://www.phys.hawaii.edu/~anita/new/papers/militaryHandbook/pwr-dens.pdf

A little more advanced:
http://didier.quartier-rural.org/implic/ran/sat_wifi/sigprop.pdf

Outcomes

- Students observe and recognise that signal strength and power decrease dramatically with distance from the source. In theory it would be an inverse square relationship. (The pattern is not necessarily a simple mathematical one, and no mathematical conclusions may be drawn other than of a very general nature.)
- Students should recognise that a signal's strength can be recorded by inducing voltages and currents in a test circuit.

Background information

The investigation is not meant to be definitive in any way. It is meant to serve as a demonstration that a signal's strength can be recorded and that is affected by distance between source and receiver.

The theory that the signal strength will decrease as an inverse square is dependent on:

- The meter reading being a true measure of signal strength, which it isn't. It makes no discrimination between the desired signal and any other signal in the environment. It is only a relative measure.
- The signal propagating uniformly in all directions. This is not a characteristic of an ordinary whip aerial.

Extensions

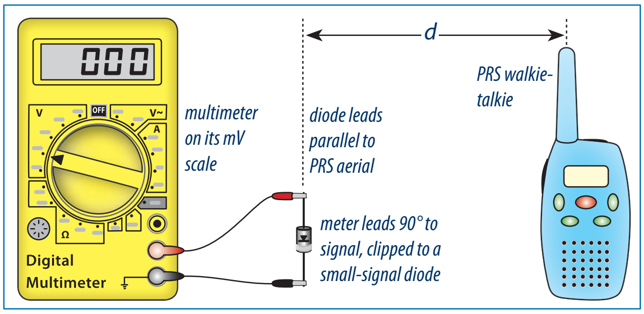
Students could estimate the radio energy output from stars ($P_{(s)}$) by researching the radio energy detected by telescopes ($P_{(d)}$) and by knowing how far away the star is (R): $P_{(d)} = P_{(s)}/4\pi R^2$

How Electromagnetic Signal Strength Alters with Distance

Radiant energy from a point source spread out in all directions in a predictable and geometric way, summarised as the inverse square law.

Procedure

The equipment is set up like this:

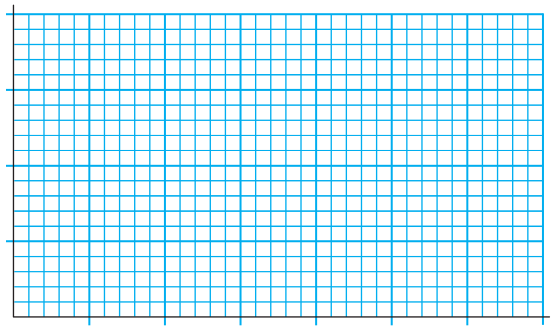


1. Arrange the leads on the multimeter so they have minimal effect. This happens when they are in a line directly away from the aerial of the PRS walkie-talkie.
2. Take a reading on the multimeter at the start, with the PRS handset turned on, but not in transmit mode. This reading is the background reading (V_1) and has to be subtracted each time from the multimeter reading (V_2). Do **not** use PRS channels 1–8, 22, 23, or 35.
3. Measure the distance of the diode from the PRS antenna, set the PRS to transmit and take a reading on the multimeter. Subtract the background reading already recorded from this to get the signal strength reading (V_s).
4. Release the transmit button on the PRS handset.
5. Gradually move the CB away from the diode, recording the separation and multimeter reading as the separation increases and repeating steps 2, 3, 4 each time.
6. Record all your results on the table provided below and complete the extra column for V_s^2 which is proportional to the energy being dissipated in the detector circuit.

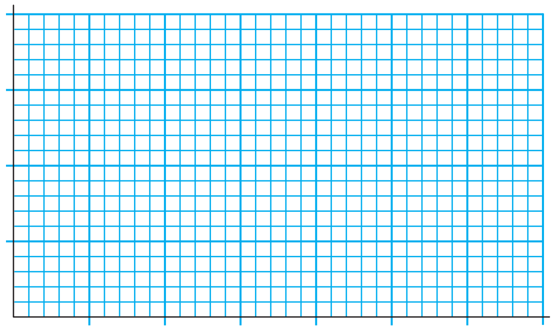
d	1/*d*	V_1	V_2	$V_s = V_2 - V_1$	V_s^2

7. Graph: (i) V_s against *d*
   (ii) V_s^2 against *d*
   (iii) V_s^2 against 1/*d*

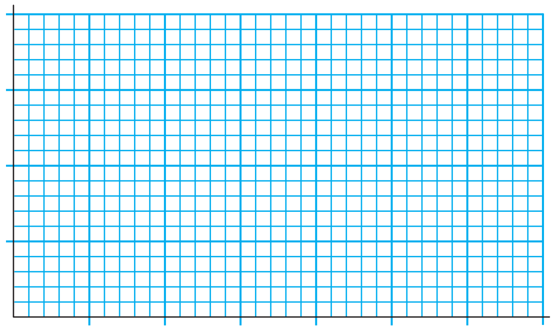
(i)



(ii)



(iii)



8. Evaluate your results and draw a conclusion from your data about how the signal energy dissipates with distance.