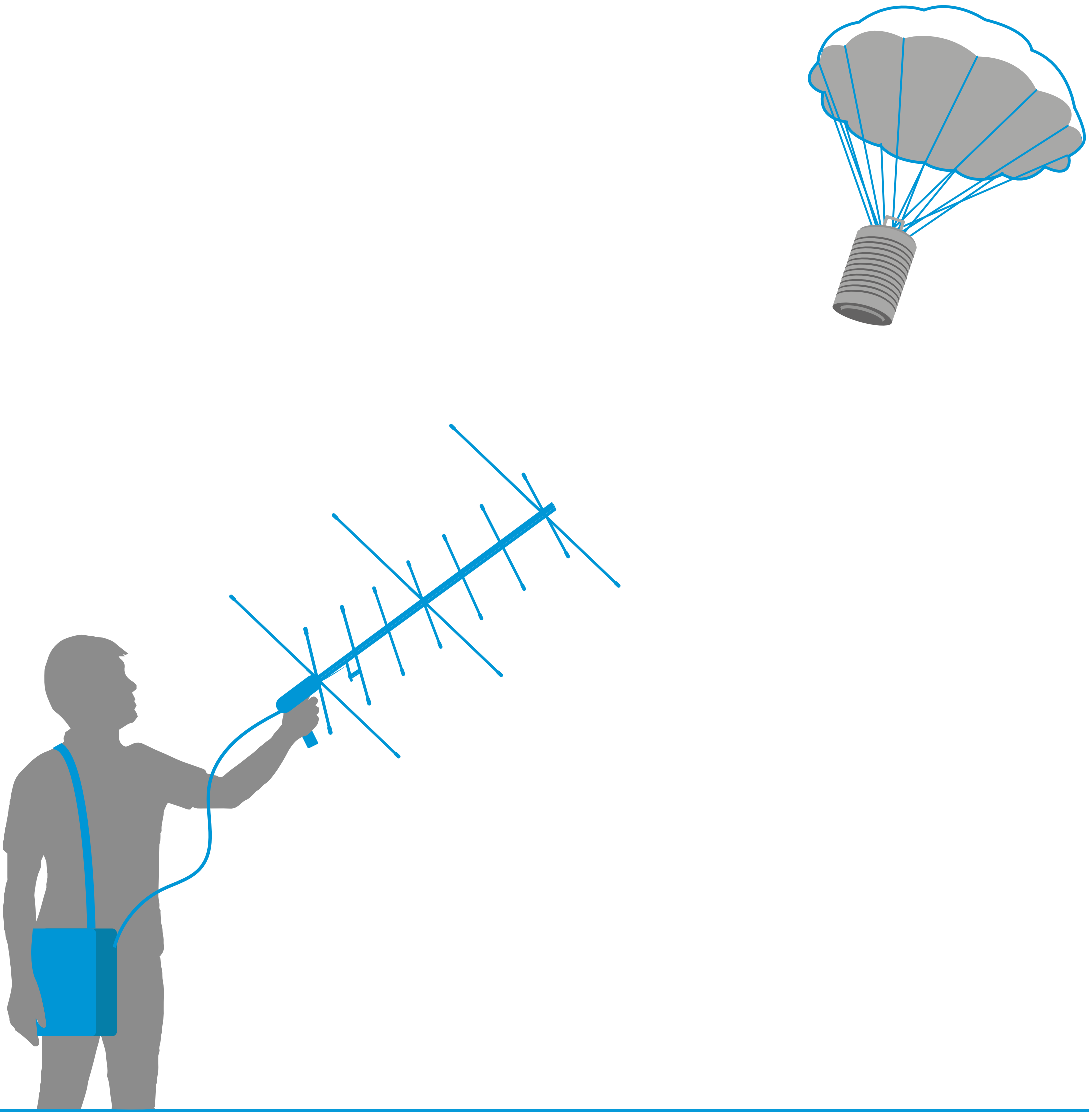
Technology | T11

teach with space

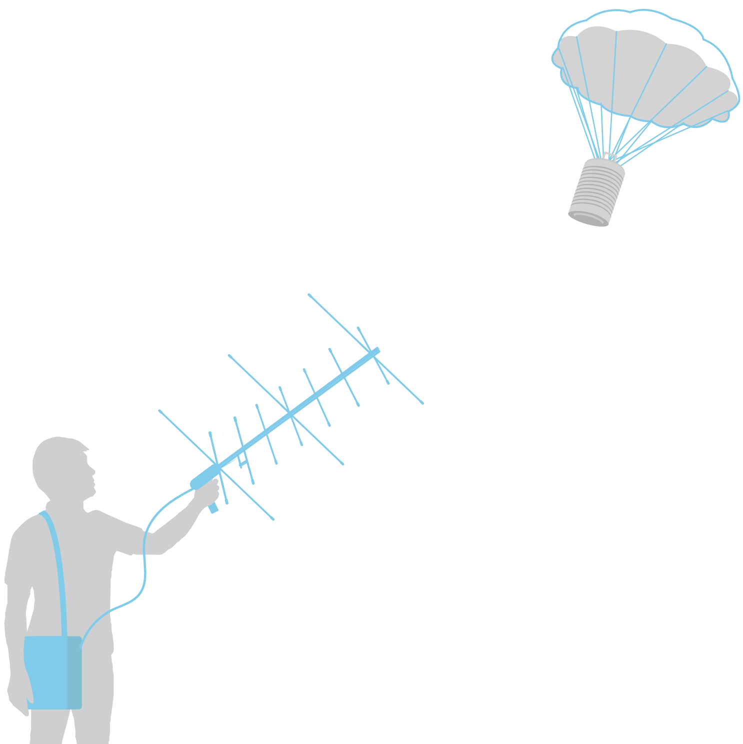
→ COMMUNICATING WITH RADIO

Ground control to Major CanSat



teacher guide & student worksheets

European Space Agency



Teacher guide

teach with space – communicating with radio | T11
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→ COMMUNICATING WITH RADIO

Ground control to Major CanSat

Fast facts

Age range: 14-20 years old
Curriculum links: Physics, Electronics
Complexity: Medium
Lesson time required: 120 minutes
Location: Indoors
Supporting resources: Getting started with CanSat
Cost: Approximately 30 euros
Keywords: Radio, Communication, Wavelength, Frequency, Spectrum, CanSat

Outline

To understand how everyday devices like mobile phones, routers and satellites work, we need to understand what radio waves are and how we can transmit information with them. Radio communication is one of the key elements in our CanSat. All the data needed for our scientific experiment will be sent from the CanSat to our ground station via radio waves once the CanSat is launched.

Learning objectives

- Understand the basics about waves and the electromagnetic spectrum.
- Understand how modulation works and why it is necessary to transmit information.
- Understand the importance of frequency and wavelength in radio wave propagation
- To be able to identify the elements needed in a communication process.
- To be able to distinguish between communication protocols.
- To be able to program their own radio module.
- To be able to make their own antenna and use it to receive information.

→ Summary of activities

Summary of activities					
	Title	Description	Outcome	Requirements	Time
1	Basics of radio waves	Introduction to radio waves and their place in the EM spectrum.	Students will understand the importance of the two key properties of a wave: frequency and wavelength.	None	10 minutes
2	Radio waves in satellites and communications	Overview of how radio waves are used in real-world communications systems.	Students will appreciate the range of uses of radio waves.	Previous activities	10 minutes
3	Choosing the ideal frequency	The importance of bandwidth and its dependence on frequency is discussed.	Students will be able to suggest which frequency should be used for several simple activities.	Previous activities	15 minutes
4	AM or FM?	The terms AM and FM are introduced and the importance of modulation of radio communications is discussed.	Students will be able to explain modulation via means of a simple analogy.	Previous activities	10 minutes
5	Receiving your data	Antennas are introduced and their role in a communications system is discussed	Students will be able to describe the basic operating principles of an antenna.	Previous activities	20 minutes
6	Testing your communications	Guidance on how to write code to test a communication system is given.	Students will be able to test and demonstrate radio communications with a radio module using code that they have written.	Previous activities	55 minutes

→ Introduction

In this resource, students will explore how radio waves are used in communications systems and appreciate how they can be useful for a CanSat project. Before they can do that, they will get to know the important features of a radio wave and the place of radio waves in the electromagnetic spectrum. They will also learn about the different types of radio wave and how each type has its own functions and uses before finally using a radio module to receive some data from their 'CanSat'.

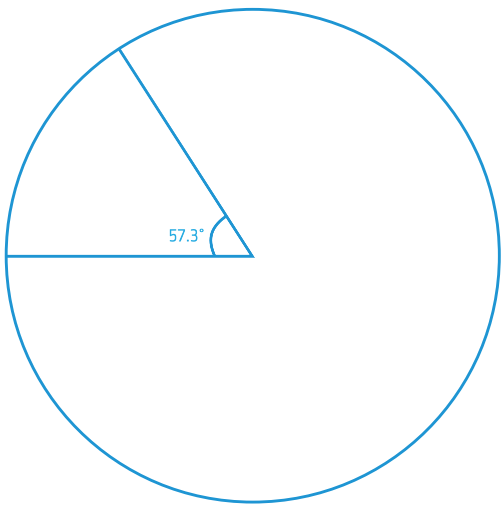
Background: Waves, a mathematical approach

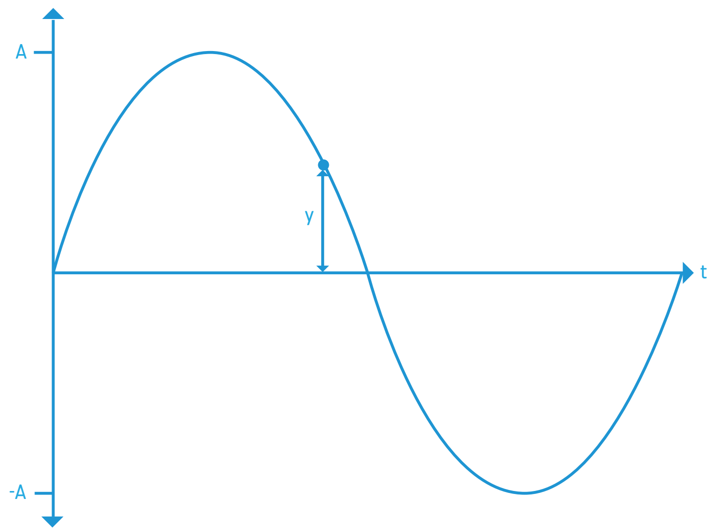
The most basic form of any wave is a sinusoidal wave of a constant amplitude A and single frequency f. The 'displacement' of the wave (y) after a time t, is therefore:

$$y = A\sin(2\pi ft)$$

The 2π term is a result of there being 2π **radians** in one 'cycle' of a sine wave. Radians are a unit we use often when we talk about sinusoidal waves. Put simply, a radian can be thought of as a measurement of an angle. Each radian is approximately 57 degrees. The time (t) has units of seconds. For a given wave, $2\pi f$ and A are constants, therefore using the above equation, it is trivial to determine the displacement (y) at any given point in time.

The two diagrams below might help you to visualise a little easier.





→ Activity 1: Basics of radio waves

In this activity students are introduced to radio waves and their place in the electromagnetic spectrum. The basic properties of a wave are introduced; wavelength and frequency.

Exercise

The students are asked to complete a table of information about radio waves. They can take estimates of the frequencies from the chart in the activity (Figure A1), or by calculating it from the wavelength values given in the text. The values given below are the latter. The values are approximate and should only be used to give a rough idea of the range of values possible.

Table 1

	Unit of measurement	Minimum value	Maximum value
Wavelength	m	0.1	10's of kilometres
Frequency	Hz	$3x10^4$	$3x10^9$

→ Activity 2: Radio waves in satellites and communications

In this activity students are introduced to the relevance of radio waves for communications and the various uses across the radio wave range. Students are asked to determine the properties of several of the commonly used radio modules in CanSat.

Exercise 1

1. **Calculate the FSPL (free-space path loss) in decibels of a typical CanSat transmitter (f of 433 MHz) at the moment of deployment of the CanSat (1km).**

   Using the equation on the student worksheet for FSPL, and substituting the given values for f and R, the answer is 85 decibels.

Exercise 2

Students are asked to complete a table of information about CanSat transmitters.

Table 2

Transmitter	Frequency	Wavelength/m	Band
APC220	418Mhz-455Mhz	0.66 - 0.72	UHF
Lora	Various (e.g. 868Mhz)	0.35	UHF
X-Bee	2.4Ghz	0.13	UHF

→ Activity 3: Choosing the ideal frequency

In this activity students are introduced to the importance of bandwidth and range when choosing a frequency for a communications device. Several simple scenarios are suggested to give some context.

1. **As every frequency has its use, let's think about which bands (low/medium/high frequency) you might use for the data transfers below:**

   Sending an S.O.S signal over several kilometres – low frequency
   Broadcasting video footage from your CanSat to a ground station – high frequency
   Sending a text message – medium frequency

   The three types of data transfers all occur over different ranges and require different rates of data transfer. Firstly, sending an S.O.S signal over several kilometres; this is a simple piece of data to transmit, but over a significant distance, so a low frequency (long wavelength) is perfect. Conversely, broadcasting video footage from a CanSat to a ground station requires a much higher bit-rate, but over a much shorter distance, so a higher frequency is preferred. A text message lies somewhere in between these two extremes, and so the medium frequency is suitable.

2. **If the so called 'sweet spot' is in the UHF band, why do satellites mainly use the SHF band?**

   SHF frequencies occupy another 'sweet spot' in the radio spectrum, as the small wavelength of these waves can be directed in narrow beam aperture antennas such as parabolic dishes and horn antennas. They are used for point-to-point communication, data links and radar.

   This wouldn't be possible with longer wavelengths (for example, in the UHF band).

   On the other hand, they are the highest frequencies which can be used for long distance terrestrial communication; higher frequencies in the EHF (millimetre wave) band are highly absorbed by the atmosphere, limiting practical propagation distances to one kilometre. The high frequency gives microwave communication links a very high information-carrying capacity (bandwidth).

→ Activity 4: AM or FM?

The concepts of AM and FM are introduced and an explanation of 'modulation' is given. The students explore a simple analogy to help them understand what modulation is.

Exercise

1. **If the so called 'sweet spot' is in the UHF band, why do satellites mainly use the SHF band?**

   Without this frequency separation it's likely that CanSat teams would pick up interference from the transmission of another team – this could jeopardise the success of the mission!

→ Activity 5: Receiving your data

In this activity the communications process in the CanSat competition is explained and the basic operating principles of antennas are discussed. In addition, students will gain a deeper understanding of the complexities of antenna. The three most commonly used types of antenna are introduced, and their differences are discussed.

Exercise

1. **What type of antenna would you choose for your ground station and which one for your CanSat?**
   The antenna on-board the CanSat needs to be isotropic (or as much as possible), which means that it transmits the same amount of power in all directions. Monopole antennas are half the size of their dipole counterparts, and hence are attractive when a smaller antenna is needed. The antenna connected to the ground station can be pointed towards the CanSat, and it can therefore be made as a high-gain directional antenna, which receives more electromagnetic waves from one direction than from another.

2. **Can you calculate the length a quarter-wave antenna needs to be to receive a 2.4GHz Wi-Fi signal?**
   Using the equation the students are introduced to in the activity:

$$L = c/4f = 3 \times 10^{8}/(4 \times 2.4 \times 10^{9}) = 0.03\text{m} = 3\text{cm}$$

→ Activity 6: Testing your communications

In this activity students use an Arduino and APC 220 radio modules to complete a simple radio communication test. For extra understanding, they are also challenged with comparing their findings with a Yagi antenna.

Exercise

1. **How far away can your partner go before you stop receiving a signal?**
   The experimental results for this exercise may vary between students.

2. **What could you change to improve the range?**
   There are several aspects that can be changed in order to improve the range of a transmission, they include:
   - Increasing the power of the transmission.
   - Reducing the frequency (increasing the wavelength).
     - o However, improvements in range from a reduced frequency are only observable on a macro scale. It is unlikely that students will be able to observe any changes within the working range of their transceivers.
   - Ensuring a clean line of sight between the transmitter and receiver.
     - o Note: This phenomena is most easily observed when the obstacles are bigger, or at least comparable to, the wavelength of the transmission.
   - Using a directed transmission (Yagi antennas).

3. **What could you change to improve the range?**
   If students try to use a quarter-wave (duck) antenna to both transmit and receive their data, they will find that the allowed range is reduced. Duck antennas are omni-directional, so their output power in any one direction is less than a Yagi antenna. Therefore, in the CanSat competition it makes most sense to use a duck antenna inside the CanSat and a Yagi antenna at the ground station.

→ COMMUNICATING WITH RADIO

Ground control to Major CanSat

→ Activity 1: Basics of radio waves

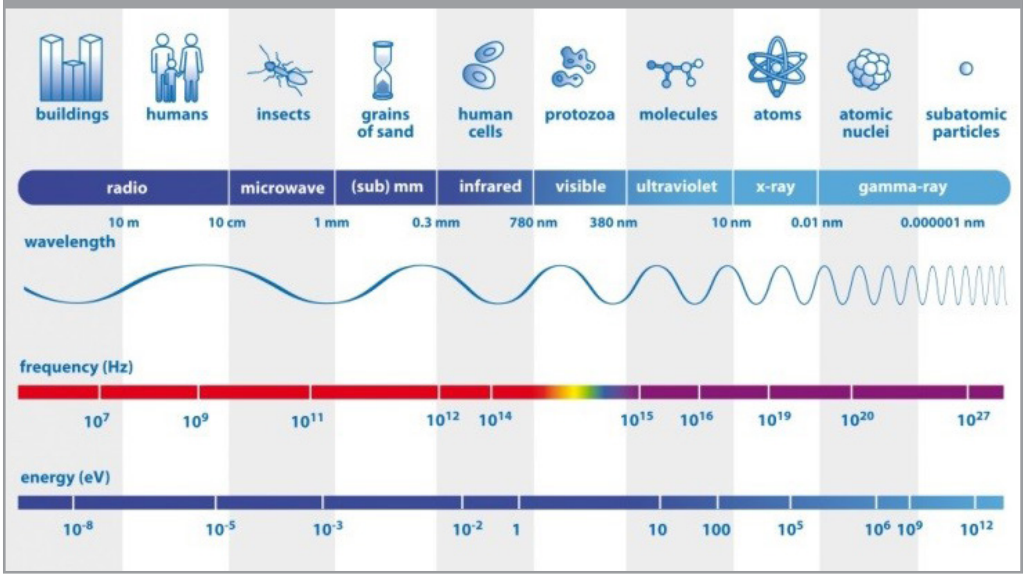
Radio waves are all around us in our everyday life, but what do we mean by a radio wave, and how are radio waves important for your CanSat mission? Lots of our day to day communication relies on radio waves, perhaps things you wouldn't expect, such as WiFi and Bluetooth – not just car radios! We will explore what exactly radio waves are and how we can use them to communicate with our CanSats.

What is a radio wave?

In any type of communication, we need a source, a carrier and a receiver and a propagation medium. A very easy example for this is oral communication: in this case, a person who is speaking is the source, the sound wave is the carrier, and the person listening is the receiver and the medium is air.

Radio communication is sending information from one place to another using a type of electromagnetic wave, radio waves. Radio waves are at the long wavelength end of the electromagnetic spectrum and, unlike sound, they can propagate in the vacuum.

Figure A1



↑ The electromagnetic spectrum

The wavelength of radio signals can range from approximately 0.1 metres up to tens of kilometres.

The frequency of a wave (which is the number of cycles per second, measured in Hz) can be calculated from wavelength using the following equation:

$$\lambda \cdot f = c$$

Where λ is the wavelength (which is the lenght of one cycle of the wave), f is the frequency and c is the speed of light ($c=3x10^8$ ms^{-1})

Exercise

Using the information and equation above, complete the table below for radio waves:

	Unit of measurement	Minimum value	Maximum value
Wavelength			10's of kilometres
Frequency			

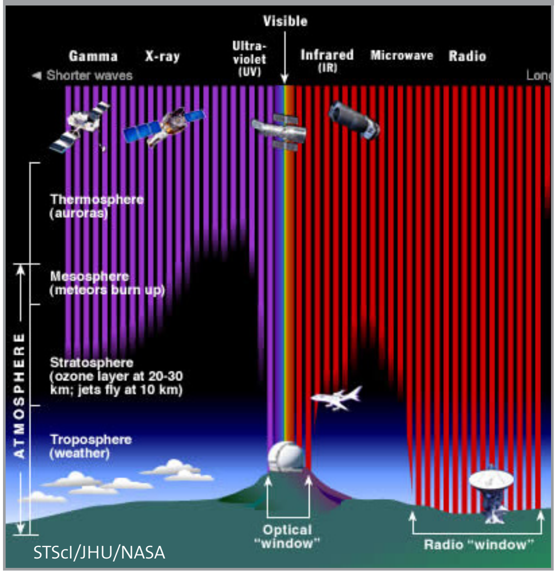
→ Activity 2: Radio waves in satellites and communications

Radio waves are perhaps the most widely used type of electromagnetic wave in communications on a day-to-day basis. But why are they so useful? In this activity we will learn about the advantages of radio waves for communications and how the frequency and wavelength chosen for our radio waves will be critical for our project.

My wave got lost!

There are only certain types of waves in the electromagnetic spectrum that are not absorbed by the atmosphere. The following image shows at what point in the atmosphere waves from space are absorbed.

Figure A2



↑ The electromagnetic spectrum

As you can see, the radio waves have a privileged place in the electromagnetic spectrum, as most of them pass through the atmosphere without being absorbed!

Radio waves, as well as some microwaves, are therefore the best option for our communications satellites in orbit to use.

Free-Space Loss

There is another aspect we need to take into account in radio communication. Free-space path loss (FSPL) is the loss in signal strength of an electromagnetic wave that would result from a line-of-sight path through free space, with no obstacles nearby to attenuate the signal. But if there are no obstacles, why do we have a loss of signal strength? Let's try an analogy:

Imagine blowing up a balloon a little and drawing a circle on it with a marker. If we try to see inside the balloon we will see that the material of the balloon is too dense to see through. Now blow up the balloon some more and redraw the same sized circle on the surface. The area we are looking at is the same, but as the balloon has expanded in all directions the material is less dense, and now we can see through it. This is a similar principle to how FSPL arises. The FSPL appears in vacuum under ideal conditions, e.g. a radio communication between satellites. The Free-Space Loss can be calculated as a ratio between the transmitted and the received power:

$$FSPL = Log_{10}\left(\frac{P_{transmitted}}{P_{received}}\right) = Log_{10}\frac{(4\cdot\pi\cdot R\cdot f)^2}{c^2} = 20Log_{10}\frac{4\cdot\pi\cdot R\cdot f}{c}$$

Where f is the transmitted frequency and R is the distance transmitter-receiver. Remember, this is the loss that occurs even in a vacuum, real world losses will be higher than this!

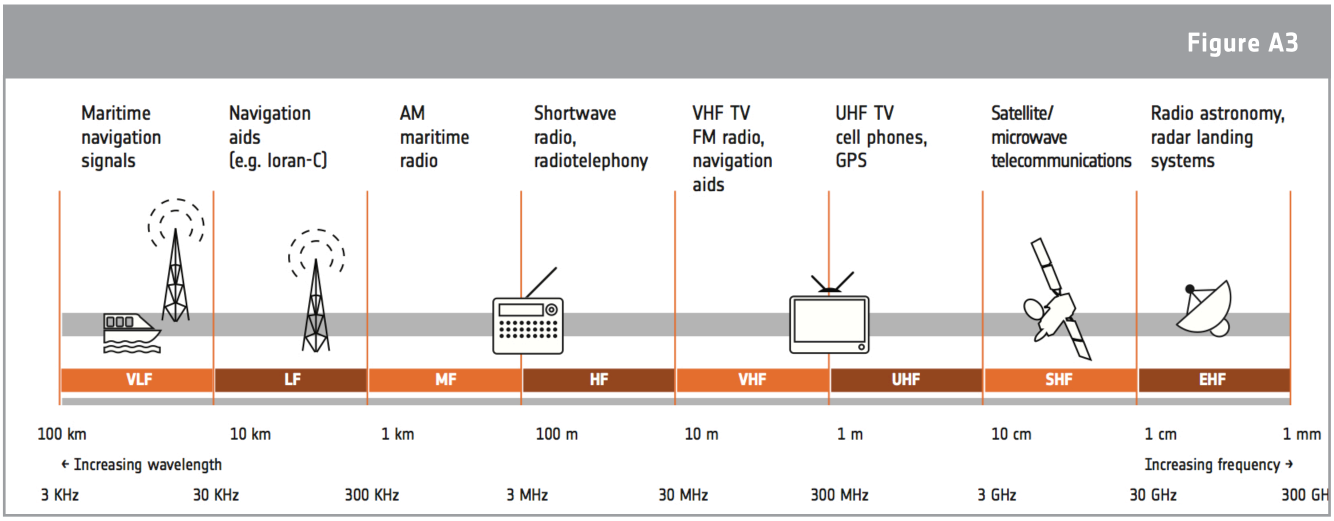
Exercise 1

1. Calculate the FSPL in decibels of a typical CanSat transmitter (f of 433 MHz) at the moment of deployment of the CanSat (1km).

Exploring the radio spectrum

Let's now explore the uses of the different types of radio waves according to their frequencies.

In the image below, we can see how radio waves of different frequencies are used in different types of communications, from maritime navigation signals, to radar landing systems.



↑ The Radio spectrum and its uses

As we see in the image, for satellite communications we use the SHF (super high frequency) band, with frequencies ranging from 2 GHz to 30 GHz, and wavelengths ranging from 1 cm to 10 cm. These waves fall within the microwave band, so radio waves of these particular frequencies are called microwaves.

Exercise 2

Complete the table below, by filling in the operating wavelengths and the band of three of the popular CanSat transmitters.

Transmitter	Frequency	Wavelength/m	Band
APC220	418Mhz-455Mhz		
Lora	Various (e.g. 868Mhz)		
X-Bee	2.4Ghz		

→ Activity 3: Choosing the ideal frequency

There are two important considerations to make when you decide which frequency to use for your communications device. The first is 'how much data do I need to transmit?'. The second is 'how far do I want to transmit my data?'. Both of these are affected by the frequency used, let's take a look at how.

The sweet spot: bandwidth vs range

In the previous exercise, you should have realised all the CanSat transceivers transmit information in the same band of the radio spectrum. But why?

Two elements play a key role in choosing our frequency; bandwidth and range.

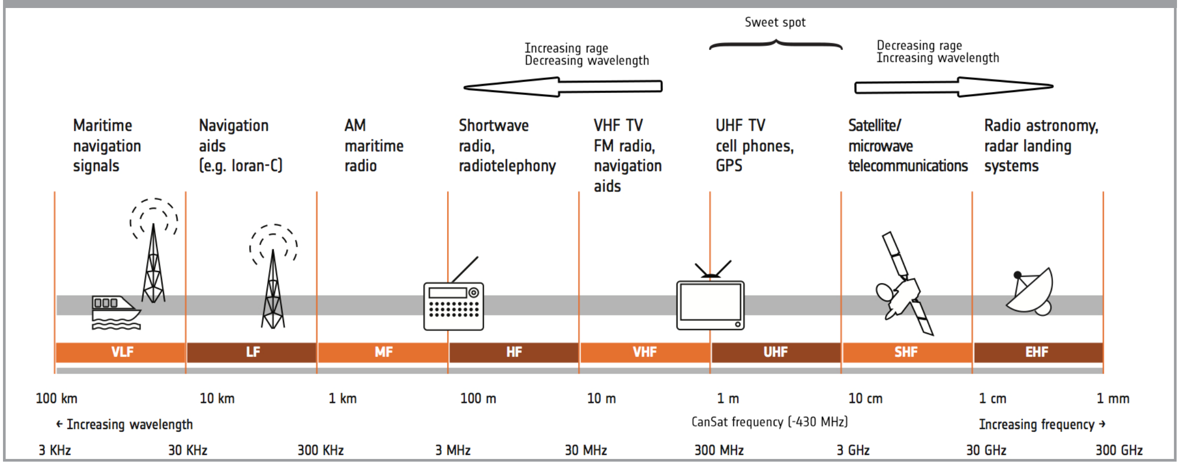
Bandwidth, measured in hertz, is the range of frequencies that the majority of the transmitter power falls between. The more information a signal must carry; the more bandwidth it needs. For example, a system that operates on frequencies between 150 and 200 MHz has a bandwidth of 50MHz (200MHz - 150MHz).

When discussing bandwidth it is important to understand two key terms: narrowband and broadband. Narrowband signals, as the name suggests, have a smaller bandwidth (in the kilohertz range). They can be used for low-speed transmissions. Broadband signals on the other hand, have a bandwidth in the megahertz range and can support much higher speed data transmissions, such as high definition video.

The range of a communications wave is the distance the wave can travel in order to be properly received. This loss is mainly from attenuation and absorption by the surroundings. In an ideal situation, all waves can travel an infinite distance (think about the light coming from stars millions of light years away for example). However, objects and the environment can absorb and diffract waves – generally, larger wavelengths require larger objects to diffract or absorb them.

The purpose of each type of radio communication is different: sometimes we want to transmit a lot of information over a short distance, other times we need to transmit very little information over a long distance. The decision to operate our CanSat in one frequency or the other, comes from analysing the objectives and characteristics of our communication.

Figure A4



↑ The Radio spectrum and its uses

In the image above, we see that the higher the frequency we choose, the broader the available bandwidth and the lower the range. This means that we can transmit much more information if we choose the higher frequency bands, but the range of our communications will be significantly less than in the lower frequency bands.

However, it's not quite as simple as that because the distance over which radio communication is useful depends significantly on things other than wavelength, such as transmitter power, receiver quality, the type, size, and height of the antenna, the mode of transmission, noise, and the presence of any interfering signals.

The frequency used in CanSat transceivers relies on what is often called the 'sweet spot', mainly the 'ultra high frequency' or 'UHF' band of the radio spectrum. Higher frequencies are not so desirable because they are highly absorbed by the atmosphere, so their range decreases, whilst lower frequencies have less bandwidth capacity.

Exercise

1. As every frequency has its use, let's think about which bands (low, medium, high frequency) you might use for the data transfers below:

   Sending an S.O.S signal over a several kilometres - ____________________

   Broadcasting video footage from your CanSat to a ground station - ____________________

   Sending a text message - ____________________

2. If the so called 'sweet spot' is in the UHF band, why do satellites mainly use the SHF band?

Did you know?

ESA operates some of the world's most sophisticated tracking stations located all over the globe, enabling spacecraft to maintain contact with Earth while voyaging deep into our Solar System. Engineers can pinpoint the orbit of a spacecraft exploring Mars or Venus - a distance of over 100 million kilometres from Earth - to an accuracy within 1 kilometre.

http://www.esa.int/spaceinvideos/Videos/2013/09/Tracking_spacecraft_deep_across_the_void

→ Activity 4: AM, FM or...?

AM and FM are two terms you might already be familiar with. You've probably come across them when listening to the radio, or perhaps you have setup a radio station of your own? But what exactly does it mean, and why is it important for our CanSat? Let's find out!

Every message needs a messenger

The 'M' in 'AM' and 'FM' stands for 'modulation', before we can explain what this means, we need to first understand two more terms:

- **Signal wave:** contains the information or message to be transmitted (e.g. humidity data)
- **Carrier wave:** the means by which information is to be transmitted (usually an electromagnetic wave, e.g. a radio wave, visible light or alternating current)

Using radio waves as the carrier waves to transfer information means that information needs to be added to the radio frequency used. Adding this information is called modulation.

Let's try a quick thought experiment to help us understand **modulation**.

Take some paper, like an envelope, and try to throw it further than 10 metres. Can you?

Now, take a medium-sized stone and wrap the paper around it. Are you able to throw it 10 metres this time?

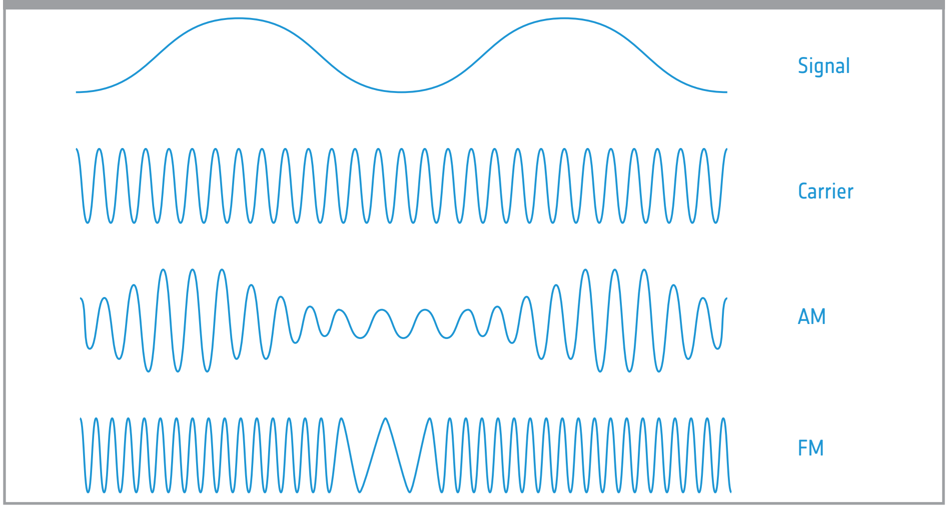
The paper enclosing the stone can achieve its goal (travel 10 metres) because we have changed one of the properties of the system. The information that we want to send (paper) can then be transmitted, by using a carrier (stone).

In electronics and telecommunications, modulation is the process of conveying a message signal, for example, a digital bit stream or an analogue audio signal, inside another signal that can be physically transmitted. In this case, we change the properties of that signal, like the frequency or the amplitude.

There are many forms of modulation, the most common however, are AM and FM.

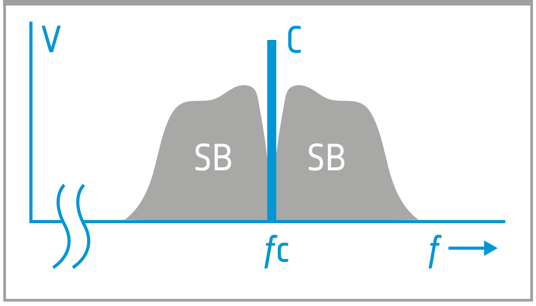
- **With AM (amplitude modulation)**, the information is transmitted by changing the amplitude of the carrier frequency.
- **In FM (frequency modulation)**, the instantaneous frequency of the carrier is changed.

Figure A5



↑ The difference between AM and FM modulation

Figure A6



↑ Modulated radio signal

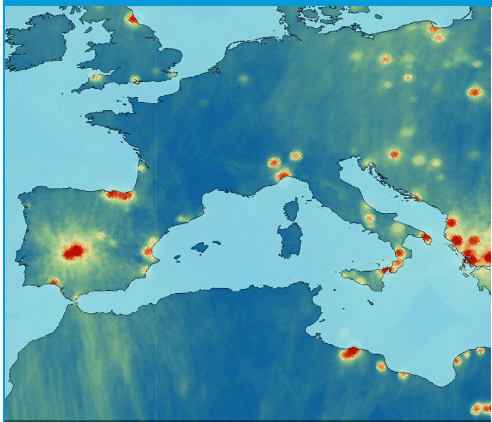
An example of what a final, modulated wave looks like is shown below. Voltage (V) is shown on the y-axis, as this is how a signal is initially measured. On-board computers are programmed to then relate the voltage to the quantity we're actually interested in.

In Figure A6, f is the frequency, fc is the carrier frequency and SB are the sidebands. You can see how the voltage of the signal falls to zero at the edges of the sidebands. The bigger the bandwidth, the wider the sidebands.

Exercise

Our everyday devices never rely on the same frequencies. You can see a few examples of everyday appliances and their operating frequencies in Figure A3 from Activity 2. Similarly, in the European CanSat Challenge, frequencies allocated to the CanSat teams are separated by at least 0.1MHz. Can you explain why?

Did you know?



16-31 January 2010

ESA's Soil Moisture and Ocean Salinity (SMOS) mission is dedicated to making global observations of soil moisture over land and salinity over oceans. When ESA's SMOS satellite was placed in orbit in 2009, it transpired that numerous illegal transmitters around the world were interrupting its signal. However, by working with national frequency protection authorities, 75% of these transmitters have now been shut down. Nevertheless, this is a laborious process and some regions, such as the Libyan coast and the eastern Mediterranean Sea, remain contaminated where mitigation strategies have not yet been successful.

So, which type of modulation should we use?

Well, we know that:

- When we amplify an AM signal, the noise gets amplified as well, a situation that won't happen with FM modulation.
- In FM modulation, the amplitude of the carrier wave is small compared to the amplitude of the side bands, so most of the power in transmission goes to the sidebands, where the information is.
- The same information can be transmitted using less power with FM compared with AM.
- The bandwidth for FM is greater than that for AM.
- The modulators and demodulators are more complex for FM than AM.

All but one of the important factors above favour FM rather than AM, and this is the reason you see it used much more in everyday life. However, both of these modulations have become old-fashioned now, as other types of modulation like FSK (frequency-shift keying), help us to transmit much more information than AM and FM. One of the most used transceivers in CanSat, the APC 220, uses this type of modulation.

→ Activity 5: Receiving your data

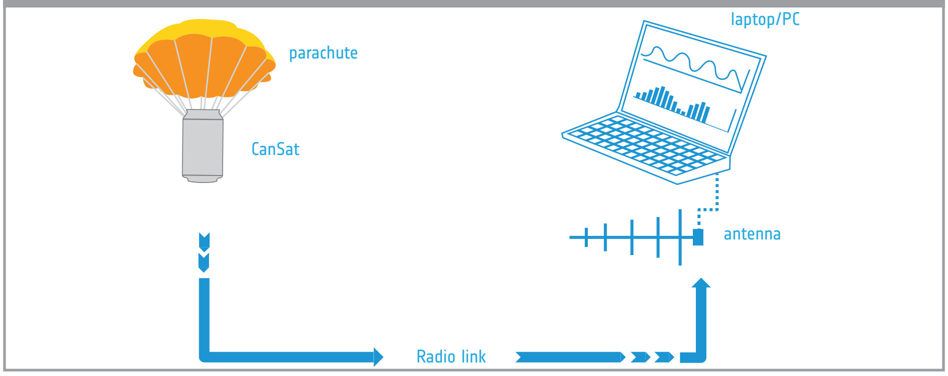
A transmitter creates an oscillating signal on a cable connected to the antenna. That signal is transformed and emitted as electromagnetic waves through the antenna. At the receiving end of the communication, part of this wave is collected and transformed back into electric current by another antenna.

Your CanSat project will involve two antennas: the first is the antenna on-board the CanSat, the second is the antenna used at the ground station. The antennas need to be made to different specifications, although the mode of operation is similar for both antennas. We need to look at the characteristics of each antenna in order to choose the best option for both the CanSat and the ground station.

Listening in on standing waves

While it's in the air, the CanSat sends information via radio waves and these waves are detected by an antenna that we hold at the ground station. This information is then processed by our code into information that we can understand, like temperature and humidity measurements. A term you will often see once you further research making your own antenna is a '1/4 wavelength' antenna. This refers to the actual dimensions of the antenna relative to the wavelength of the wave you are trying to receive. When the wave interacts with the antenna, standing waves of electrons are created inside the metal. The orientation and length of the antenna ensures that the final standing wave accurately reflects the incoming wave. This movement of electrons (a current) can then be interpreted by a computer.

Figure A6



↑ Communications scheme CanSat-Ground Station

Devices that contain radio receivers include television sets, radar equipment, two-way radios, cell phones, wireless computer networks, GPS navigation devices, satellite dishes, radio telescopes, Bluetooth devices, garage door openers, and baby monitors.

The quality of the radio link depends mainly on three aspects: the transmitter power, the receiver sensitivity and the antennas used. All of these can be changed with the selection of the transmitter and antennas that you use.

Did you know?

This is ESA's Hertz Hybrid European RF and Antenna Test Zone for antenna testing at ESTEC, formerly known as the Compact Payload Test Range. Metal walls screen outside radio signals while spiky foam interior cladding absorbs radio signals internally to create conditions simulating the infinite void of space.

Exercise

1. What type of antenna would you choose for your ground station and which one for your CanSat?

Types of antennas

Three common antenna types are the quarter-wave antenna, the duck antenna (or rubber duck) and the Yagi antenna; we'll now explore all of these in more detail.

CanSat antenna type 1: Quarter Wave antenna:

A very common form of antenna is a **monopole antenna**. A monopole antenna is an antenna with a straight rod-shaped conductor, the most common of which is the **quarter-wave antenna**. The reason behind the name is quite simple: the length of the conducting rod is one quarter the wavelength of the (radio) wave it will receive or transmit!

The required length of a quarter-wave antenna can therefore be calculated using the following equation:

$$L = \frac{c}{4f}$$

Where:

L is the required antenna length	[m]
c is the speed of light (3×10^8 km/s)	[m/s]
f is the operating frequency	[Hz]

The formula shows that the length of the antenna for a 434 MHz receiver should be around 17.3 cm. The wire can be soldered to the antenna contact of the transmitter board directly, or, when using a coaxial cable, the antenna can be placed some distance away from the board. When using a coaxial cable, the last 17.3 cm of the outer conductor would need to be removed to form the actual ¼-wavelength antenna. It needs to be protected with insulation material, as electric contact with metal surfaces might damage the transmitter.

Exercise

2. Can you calculate the length a quarter-wave antenna needs to be to receive a 2.4Ghz Wi-Fi signal?

CanSat Antenna type 2: Duck antenna

Figure A7

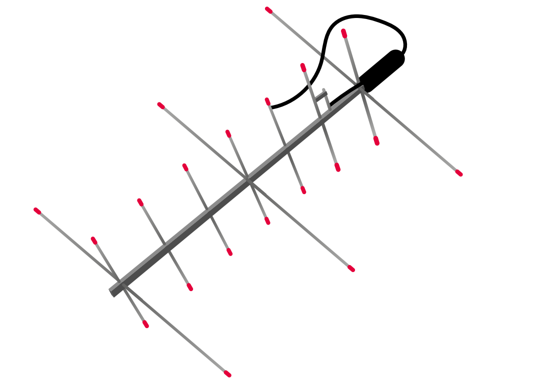
↑ Duck antenna

A 'duck' antenna is likely the type of antenna you are most familiar with, it is the type you will find on the back of your household routers and broadband modems. Inside the plastic casing of a Duck antenna is a metal helix, this is used to receive or transmit the signal. This is the antenna type that is normally included in the CanSat kit.

Ground Station antenna: Yagi Antenna

Another type of antenna that you will be familiar with is a Yagi antenna. This is the antenna that is often found connected to old fashioned televisions and on rooftops that receive analog television signals. The figure below shows a directional Yagi antenna that operates at two different frequencies. The antenna has a seven element Yagi for 433MHz and a three element Yagi for 145MHz. Notice how the orientation of the two sets of elements is different, ensuring that the standing waves formed do not interact with one another. For receiving the CanSat radio waves, building a Yagi antenna is a good option as it can be constructed relatively easily, using cheap materials such as wood and copper tubes.

Figure A8



↑ An "Arrow" which is a Yagi antenna for operation at 2 different frequencies

The CanSat antenna needs to be sufficiently robust to survive the launch on a rocket. Due to the size restrictions, a quarter-wave wire antenna works very well for our CanSat. The quarter-wave describes the length of the antenna in reference to the operation frequency. The transmitters of the CanSats normally work at around 433MHz, though the precise frequency assigned to your team in the European competition will be typically in a range from 433-435MHz. This is done to protect each team from interference, due to all the other team's CanSats.

Building a Yagi antenna

Yagi antennas are very common and are the antennas of choice for many CanSat teams. You are however, free to use different designs and approaches if you wish. The radio module used in your CanSat will be a much more individual decision, based on the objectives of your mission and your available budget and space. It is vital that you look at the technical specifications of the module you are considering before purchasing it, to ensure it is suitable for your mission!

The main structure of a Yagi antenna is shown in the Figure A8. It is vital that the distance between each of the so called 'parasitic elements' and the length of each is calculated accurately (there are many online tools to help you do this!). The parasitic elements must be electrically conductive (a metal rod is perfect) but not electrically connected to the other components.

A detailed step by step guide on how to build a basic 430 MHz Yagi antenna can be found here: https://www.youtube.com/watch?v=2paNzKMW-8c. If you have a printed version of this document, you can also write 'DIY Yagi-Uda Antenna' in the youtube search function in order to find this video.

No pain, no gain

The antenna's gain is a key performance number which combines the antenna's directivity and electrical efficiency. In a transmitting antenna, the gain describes how well the antenna converts input power into radio waves headed in a specified direction. In a receiving antenna, the gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power. When no direction is specified, "gain" is understood to refer to the peak value of the gain, the gain in the direction of the antenna's main lobe. A plot of the gain as a function of direction is called the radiation pattern.

Power gain (or simply gain) is a unitless measure that combines an antenna's efficiency E (calculated from input power P_{in} and the output power P_o) and directivity D:

$$G = E_{antenna} \cdot D = \frac{P_0}{P_{in}} \cdot D$$

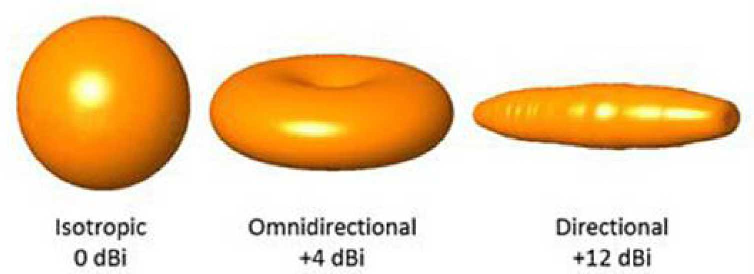
Whereas the gain in decibels is calculated as follows:

$$G_{decibels} = 10 \cdot log_{10}(G)$$

When the directivity is converted to decibels we call it the antenna gain relative to an isotropic source (dBi). Typically the higher the gain, the more efficient the antenna's performance, and the greater the range over which the antenna will operate. For every 6 dBi in gain, you double the range of the antenna.

As you can see in the images, directional antennas (like the Yagi antenna) have a higher gain but their drawback is that they will only be able to strongly emit or receive radio waves in an specific direction. However, omni-directional antennas(e.g. monopole) have a lower gain in decibels but they can emit or receive around 360 degrees.

Figure A6



↑ Examples of different antennas power patterns with their power gain in decibels.

Yagi-Uda antenna gain considerations

A number of features of the Yagi design affect the overall gain:

Number of elements in the Yagi: One of the main factors affecting the Yagi antenna gain, is the number of elements in the design. Typically a reflector is the first element added in any yagi design as this gives the most additional gain. Directors are then added.

Element spacing: The spacing can have an impact on the Yagi gain, although not as much as the number of elements. Typically a wide-spaced beam, i.e. one with a wide spacing between the elements gives more gain than one that is more compact. The most critical element positions are the reflector and first director, as their spacing governs that of any other elements that may be added.

Antenna length: When computing the optimal positions for the various elements it has been shown that in a multi-element Yagi array, the gain is generally proportional to the length of the array. There is certain amount of latitude in the element positions.

→ Activity 6: Testing your communications

Now that we understand the complexities of radio communication we're ready to build and test a full communications system! In this activity we will perform some simple tests using APC220 transmitters and a duck antenna.

Receiving data

There are many different transmitters and receivers available for you to use in your CanSat, and we can't cover them all in detail. In this section, we're going to explore using APC220 transmitters to send and receive some information!

Note: The instructions below may not work perfectly for your exact configuration. Your operating system, Arduino version, Arduino board and the transmitter chips you use are all important. If you have problems, consult the manufacturer's data sheets and instructions.

Step 1: The elements

As well as your Arduino board and a computer, you will also need a set of APC220 transmitters, two duck antenna and a suitable USB-TTL converter. In this guide, we are using the PL-2303 USB-TTL converter.

Note: You will also need a second laptop, or an external power supply for your Arduino.

Step 2: The drivers

In order for the USB-TTL converter to interface with your computer, you will first need to install the drivers. Links to the drivers can be found here: https://www.dfrobot.com/wiki/index.php/APC220_Radio_Data_Module(SKU:TEL0005)#Communication_Test

Note: There are known problems with Windows 8/10 devices and the PL-2303HXA and PL-2303X USB-TTL converters. If your computer does not recognise the device, check the version numbers. Once you have installed the drivers, check that the device is recognised by going to Start -> Device Manager and looking for it in the 'Ports' section. If it is not listed, try rebooting your PC and checking again.

Step 3: Pairing the transmitter and receiver

The next step is to configure both APC220 devices so that they are tuned in to the same frequency, and sending/receiving at the same rate, otherwise the two will not be able to communicate with one another.

To do this, we will use a special Arduino sketch that can be uploaded to the UNO and used to configure the devices.

Firstly, download the APC220 config '.ino' file

Next, open and upload the code to the Arduino.

Now, connect the APC220 to the Arduino Uno as shown in the photo below (from digital pin 8 to GND):

Once the APC220 is connected, open the 'serial monitor', a menu should appear, if it does not, type 'm' in the command line and press enter.

The menu gives instructions on how to configure the APC220. The most important point is to make sure that you configure your pair of APC220s to the same frequency, baud rate etc.

Note: If you have a class with many sets of APC220s it is a good idea to set each pair to a different frequency, unless you want to listen in on other groups' messages! Remember the working range of the APC220 is 420-450Mhz.

An example of a command to configure the APC220 is also given and explained in the menu.

Step 4: Time to test!

We are now ready to try to send and receive some data.

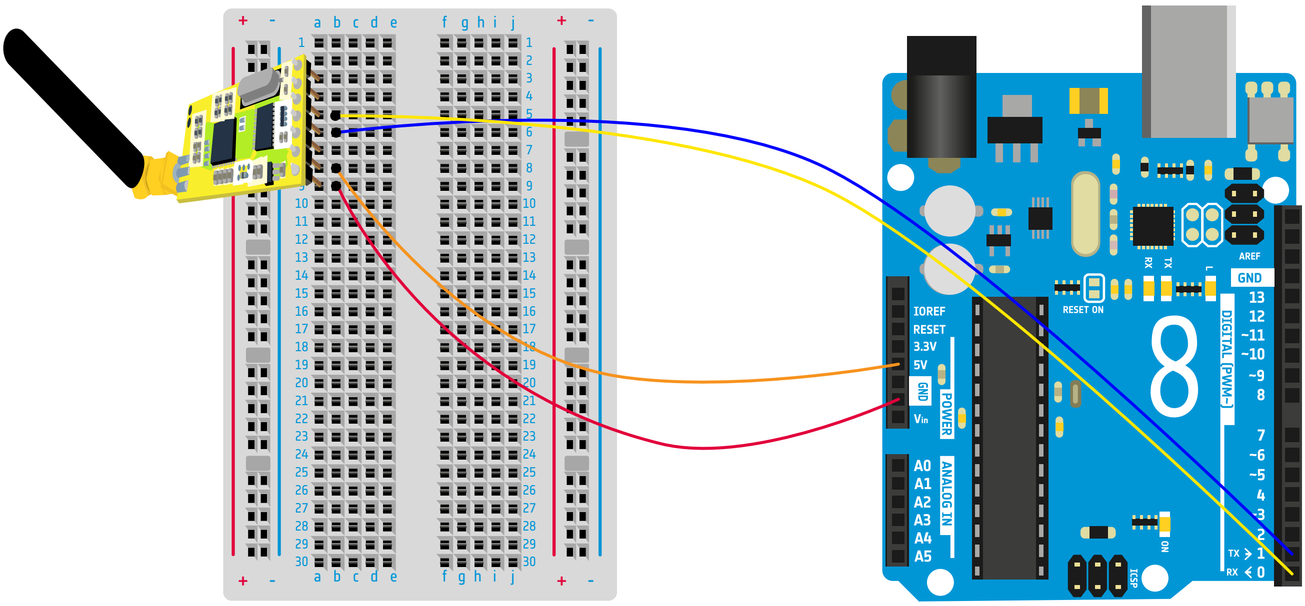
To do this we need to use two pieces of software, the Arduino IDE, which you are familiar with, and 'Serial Port Utility' can be downloaded here.
Note: There are many different pieces of software you can use to read the serial port, feel free to use any you are comfortable with!

Firstly, connect your Arduino board and send the code below to it.

```
void setup()
{
  Serial.begin(9600);              //Set serial baud rate to 9600
}

void loop()
{
  Serial.println("Hello!");            //print out hello string
  delay(1000);                   //1 second delay
}
```

Now, disconnect the Arduino from the computer and set up the circuit as shown in the figure below.



Once the circuit is set up you can connect it to an external power supply (you cannot connect it to the laptop you will use to receive data to, as it will interfere).

Finally, connect the other APC220 to your computer via the USB-TTL converter and open the Serial Port Utility.

Congratulations! You should now see the message 'Hello!'. If you don't see the message, check that you are reading the correct COM port and that the Arduino IDE is closed.

You can extend this by incorporating measurements into your code, and adding timestamps, so that the original data can be verified.

Exercise

Let's test the capabilities of our transmitters and receivers! Once you're confident you can transmit data following the guide above, have a partner move away from the transmitter with the receiver.

1. How far away can your partner go before you stop receiving a signal? _______________

2. What could you change to improve this?
   Think about everything we have discussed in this resource so far!

3. Build a Yagi antenna and repeat the tests. If you have access to them, use the three radio modules introduced in activity 2. What is the main difference between the Yagi and the quarter-wave antenna?

→ Links

An example of an easy to build WiFi Antenna
instructables.com/id/Easy-to-Build-WIFI-24GHz-Yagi-Antenna/

Information on the APC220 radio module
dfrobot.com/wiki/index.php/APC220_Radio_Data_Module(SKU:TEL0005)

An example of where to purchase a 433MHz LoRa radio module
amazon.co.uk/Adafruit-Feather-RFM96-LoRa-Radio/dp/B071V71ZSD/