ROYAL SCHOOL OF ARTILLERY

BASIC SCIENCE & TECHNOLOGY SECTION

Basic Radar Theory

INTRODUCTION

The concept of creating a wave, waiting for it to travel out to a distant object, reflect from the object and, finally, return to the source as an echo is hundreds of years old. Masters of sailing ships would fire a cannon at night or during foggy weather, if they suspected that the ship was too close to a rocky shore. The audible echo would give warning of nearby cliffs. Sound travels approximately one kilo-metre in three seconds, so an echo that arrived back after six seconds would indicate that the shore was about one kilo-metre away. (The echo makes a two-way trip of total length two kilometres, so the distance to the shore is one half of that.) The ship's master could count the seconds in his head and no special equipment was needed to estimate the distance to the shore.

Radars use radio waves (electro-magnetic waves) and they travel at the speed of light, 3×10^8 ms^{-1}. These waves take about 3.3 micro-seconds to travel one kilo-metre and require electronic devices to measure the time taken to travel from source to object and return. However, the basic concept is the same as that used by the ship's masters, hundreds of years ago.

The theoretical possibility of Radar (**RA**dio **D**etection **A**nd **R**anging) was predicted by Maxwell as early as 1873, but it was only developed for military applications in the years leading up to World War Two. By 1938, the 'Chain Home' Radar System was in use for coastal air defence and the development of radar proceeded rapidly after war began. Later, the Cold War provided another spur to the development of radar, leading up to the military radar systems that are in use today.

REFLECTIONS, TARGETS, CLUTTER AND NOISE

The EM-Waves that are used for ordinary radar have frequencies of a few Giga-Hertz and the corresponding wavelengths are a few centimetres (remember that Frequency in GHz multiplied by Wavelength in cm comes to 30).

Strong Reflection: EM-Waves of radar frequencies are readily reflected by metallic objects, falling rain, the terrain, etc., and give rise to strong radar reflections because these materials are conductors of electricity.

Weak Reflection: All materials, including insulators, will also reflect EM-Waves because the material has different properties from those of the surrounding air. The differences in electrical properties between the material (e.g. fibre-glass) and the surrounding air might be quite small and so the amount of reflection is much less that produced by electrical conductors.

Echo: the radar echo is the term used to describe the radar signal that is reflected by any object. Generally, the echo signal in a practical radar might be only a fraction of a millionth of a Watt. This is a consequence of the great distance that the signal has to travel - just like the ripples on a pond, the waves spread-out as they move further away from their source.

Target: a radar target is an object of interest that reflects radar signals.

Clutter: clutter is the term used to describe radar echoes that arise from objects that are of no interest to the radar system. An air-defence radar would treat echoes from the terrain as clutter whereas a ship's captain would want to see such echoes so that he could avoid the rocks and navigate safely into harbour.

Noise: produced mostly by thermal energy, this is a random signal that might either mask a radar echo or be mistaken for one. For effective radar operation then the radar echo must be much greater than the noise. (Imagine how difficult it would have been for the ship's master to hear the echo of his cannon during a howling gale.)

Part of the task of a radar system is to be able to distinguish the echoes from targets from those produced by clutter and noise. In ground-based, air-defence radars, for example, the targets can usually be distinguished from the clutter by their Doppler Shift.

TYPES OF RADAR

There are several, distinct types of radar and each has been designed for a specific rôle. A summary of the main types is below:

- **Pulsed Radar**: the common form of radar. This uses the time between sending out a pulse and receiving the echo to determine range. Generally, a single antenna is used both for transmitting and receiving.
- **Continuous Wave Radar**: used where range is not required, this type of radar is used to measure velocity by detecting the Doppler Shift. Generally, this type of radar requires two antennae: one for transmitting and another for receiving.
- **Primary Radar**: the radar relies on reflections from the target. The target is passive. This is the common type of radar.
- **Secondary Radar**: a transponder in the target replies to interrogations from the radar. This is the basis of the IFF System.

USING PULSED RADAR TO MEASURE RANGE

The pulsed radar emits pulses of EM-Waves and waits for an echo from the target. The waves travel 300 metres each micro-second so an echo that returns after one micro-second would have come from a target that is 150 metres away (a round-trip of 300 metres in one micro-second). This illustrates the fundamental rule of radar ranging that one micro-second of 'radar time' is equivalent to 150 metres of range.

A delay of 10 µs would correspond to a range of 1.5 km and a delay of 100 µs represents a range of 15 km. Always use the rule that the delay in micro-seconds is multiplied by 150 to give the range in metres. The general rule, using the velocity of light (c) and the time delay of the radar signal (t_d) is given in the side-bar.

Example 1: An echo from a target is received after a delay of 33.2 µs. What is the range of the target?

The range is 33.2 × 150 = 4980 m = 4.98 km.

Example 2: An echo is received after a delay of 0.22 ms. What is the range of the target?

The delay in micro-seconds is 0.22 × 1000 = 220 µs.
The range is 220 × 150 = 33000 m = 33 km.

PULSE DURATION

The radar pulse that emerges from a radar transmitter must last for some interval of time and that is called the 'Pulse Duration' (sometimes called pulse width). Typically, the pulse duration is a few micro-seconds, e.g. 10 µs, although some specialised radars might use shorter or longer pulses. During the pulse, the transmitter might be producing EM-Waves with an intensity of several kilo-Watts, e.g. 3 kW.

PULSE INTERVAL

After each pulse is transmitted then the radar receiver listens for any echoes. During this time, the transmitter must be switched off otherwise it would damage the sensitive receiver, in addition to masking any echoes. The time interval between the transmission of one pulse and the transmission of the next pulse is called the pulse interval.

The pulse interval that is used in a radar depends, to some extent, on its operating range. As shown in Example One, above, a target at a range of 5 km will produce an echo with a time delay of about 33 µs. Example Two shows that a target at a range of 33 km produces an echo after 220 µs. From this, you could deduce that short-range radars can use a short pulse interval whereas long-range radars require a long pulse interval. A typical Pulse Interval might be 100 µs.

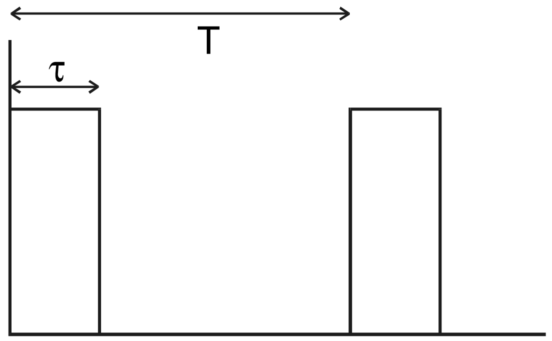


Figure 1: Illustrating Pulse Duration (τ) and Pulse Interval (T) for a Radar System

GENERAL RULE FOR RADAR RANGE

The general formula for calculating radar range relates the range in metres 'R', the time delay in seconds 't_d' and the velocity of light 'c' as follows:

$$R = \frac{c \times t_d}{2}$$

The useful rule that each micro-second represents 150 metres of range is derived from the above formula.

Figure One shows the pulse duration and pulse interval in graphical form. The symbol used for Pulse Duration is a Greek letter 'τ' (pronounced 'tor') and the symbol for Pulse Interval is 'T'. The diagram of Figure One does not actually show the transmitted waveform. This graph is called the 'Envelope' of the waveform and it shows the outline of the wave, not its detail. The graph of Figure Two illustrates the type of waveform that is actually transmitted.

Number of Cycles per Pulse: a typical radar frequency would be 3 GHz - this means that there are 3 000 Million cycles in each second The pulse duration is 10 µs so the number of cycles of radar wave in a pulse is 10 µs × 3 GHz = 30,000.

The general formula for the number of cycles (n) of radar wave in each pulse is:

$$n = \text{Pulse Duration} \times \text{Radar Frequency}$$

There will usually be several thousand cycles of the radar wave in each pulse, depending on the type of radar. Figure Two is not to scale and shows only a few cycles for clarity. If several thousand cycles were shown then the diagram would print a solid black because the lines would overlap.

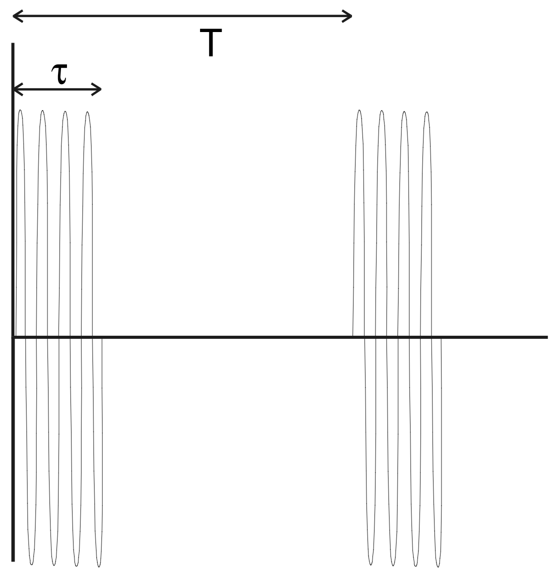


Figure 2: Illustrating the Waveform of the Transmitted Pulse

DUTY CYCLE

It should be clear from Figures One and Two that the radar transmitter actually transmits for only a small fraction of the time. In the case of the 'typical' radar described above, with a Pulse Duration of 10 µs and a Pulse Interval of 100 µs then the transmitter is on for 10 µs in every 100 µs - that represents ten percent of the available time. This figure is called the Duty Cycle and it can be expressed as a percentage (10%), as a fraction (1/10) or as a decimal (0.1). The percentage form is the one that is most commonly used.

Duty Cycle is defined in general terms using the following formula:

$$DC\% = \frac{\text{Time On}}{\text{Total Time}} \times 100\ \%$$

In radar terms:

$$DC\% = \frac{\text{Pulse Duration}}{\text{Pulse Interval}} \times 100\ \%$$

Example 3: An radar transmits for 6 µs every 120 µs. What is its Duty Cycle?

The DC is 6 ÷ 120 × 100 = 5%

Example 4: An radar transmits for 2 µs and listens for 48 µs. What is its Duty Cycle??

The Total Time is 50 µs and the On Time is 2 µs so the Duty Cycle is 2 ÷ 50 = 1%.

***Note**: the 48 µs is the gap between the pulses - this is not quite the same as the Pulse Interval, see Figure One. The Pulse Interval is the gap between the pulses PLUS the Pulse Duration. The old terms for pulse duration (mark) and gap between pulses (space) are seldom used today, but you might meet them in older texts.*

MEAN POWER

A radar transmitter that produces, say, 3 kW using a Duty Cycle of 10% is, clearly, not operating constantly at 3 kW. For 90% of the time is is operating at Zero power. The power level during the pulse is often called the Peak Power of the radar, but it is not truly representative of the power that is being used.

The mean, or average power, is that level of power which, if it were operating continuously, would produce the same overall output as the pulsed power. This can be calculated by multiplying the Peak Power by the Duty Cycle.

Mean Power = Duty Cycle × Peak Power

In this case, the figures were a Peak Power of 3 kW and a Duty Cycle of 10%, so the Mean Power is:

Mean Power = 10% × 3 000

= 300 W.

The Mean Power is useful to compare the output of one radar system against another, as it represents the real output of the radar transmitter.

Example 5: A radar transmits a 5 kW pulse with a duty cycle of 2%. What is its mean power?

Mean power = Duty Cycle × Peak Power
= 2% × 5 000
= 100 W.

Example 6: A radar transmits a pulse of peak power 12 kW using a duty cycle of 1%. What is its mean power?

Mean power = Duty Cycle × Peak Power
= 1% × 12 000
= 120 W.

One feature of most radar systems is that the transmitter operates above its 'normal' level whilst transmitting the pulse. During the few micro-seconds whilst this takes place, the transmitter will get hot - but 10 µs is too short a time for the devices within the transmitter to heat up by a large amount. During the much longer listening time, which is 90 µs in our example, the transmitter is cooled back to a safe temperature by its cooling system.

PULSE REPETITION FREQUENCY (PRF)

This is the number of pulses that the radar emits in one second, sometimes given the symbol f_r. This number can be found by using the following formula:

$$PRF = \frac{1}{\text{Pulse Interval}}\ \text{Hz}$$

This formula may be transposed to make the Pulse Interval the subject, as follows:

$$\text{Pulse Interval} = \frac{1}{PRF}\ \text{seconds}$$

Thus, for the typical radar that we are using as an example, the Pulse Interval of 100 µs gives a PRF of:

$$PRF = \frac{1}{100\ \mu s}\ \text{Hz}$$

= 10 kHz or 10 000 pulses per second

Example 7: A radar operates with a pulse interval of 200 µs. What is its pulse repetition frequency (PRF)?

The PRF is 1 ÷ 200 µs = 5 kHz (or 5 000 pulses per sec).

Example 8: A radar operates at a PRF of 2 kHz. What is its pulse interval?

The Pulse Interval is 1 ÷ PRF = 500 µs.

COMPONENTS OF PULSE RADAR

A basic, pulsed-radar system is illustrated in Figure Three. A radar system (or simply, a radar) has many parts or subsystems. This is analogous to the 'human' system which has, as subsystems, a nervous system, an arterial system, a digestive system, etc. Similarly, the radar system has subsystems such as the receiving system, the timing system and the transmitter system. The main parts of a simple, pulsed-radar system are as follows:

- **Timer**: the timer produces a signal that marks the transmission of the outgoing radar pulse. The receiver uses this signal to initialise its clock as it begins its wait for the returning echo.
- **Oscillator**: the oscillator produces the radar-frequency signal (e.g. 3 GHz). It might include an amplifying device (e.g. Klystron or Travelling-Wave Tube) to produce the required power.
- **Receiver**: the receiver converts the radar echo into a signal that can be used by the display or computer. It will be 'tuned' to the same frequency that was transmitted.
- **Duplexer**: most pulsed radars use the same antenna for transmitting and receiving. Whilst the outgoing pulse is being transmitted (e.g. for 10 μs) the transmitter requires to be connected to the antenna. For the remainder of the time (e.g. for 90 μs) the receiver must be connected to the antenna. The duplexer performs this function. It is essential that the high-power, outgoing pulse (e.g. 3 kW) does not reach the receiver, as it will damage the sensitive circuits there.
- **Display**: older radar systems would display the radar echoes directly on a display unit and would then rely on the trained eye of the operator to classify targets, clutter, etc. Modern radar systems use computer-driven displays (VDUs) and the computer decides what appears on the display. Echoes that the computer decides are unimportant are suppressed. The computer can also include descriptive information on the display (e.g. range, course, speed, target number, whether hostile or not).
- **Power Supplies**: each component of the radar will require electrical power to function. The transmitter might require 5 000 V and 3 A whilst the receiver might require a few dozen Volts and a few Amps. The power supply contains transformers and rectifiers to convert the standard, ac supply (e.g. 200 V, 400 Hz) into those that are required by each unit.

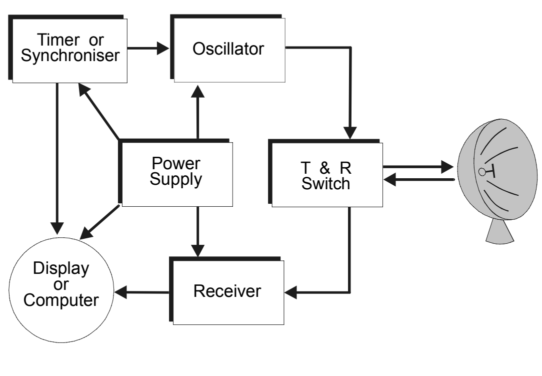


Figure 3: Block Diagram of a Pulsed Radar

RADAR DISPLAYS

There are several types of radar display that can be used. The amount and type of information that can be obtained from the display will vary according to the type of radar in which it is used and the task that the radar was designed to perform.

'A'-Scope: one of the first was the 'A'-Scope which was used for direct display of the envelope of the radar echo and its time of arrival. The antenna was first steered to a particular azimuth and then the 'A'-Scope would display information about targets on that azimuth only. The horizontal scale, from left to right, is time (from which range can be deduced using the 150 m per micro-second rule) and the vertical scale is signal strength (from which an indication of target size can be deduced). The 'trace' on the screen was produced by an electron beam that started from the bottom, left-hand side, began moving when the outgoing pulse was transmitted and traced across the screen to give the pattern of signal strength received in the next few hundred micro-seconds. A sample 'A'-Scope display is shown in Figure Four. There is no azimuth information displayed, the current azimuth is the direction in which the antenna is pointing.

Noise: one feature that you should note about all radar systems is that there might be very little difference in signal strength between a weak echo from a target and the noise produced internally by the receiver. Early radar displays were green and the little spikes of noise were called 'grass' because that is what they looked like. The radar operators learned to distinguish echoes from noise because the echoes were persistent and remained at the same position on the screen, whereas the noise was random and seldom appeared twice in succession at the same position.

'B' & 'C'-Scopes: it is also possible to plot range against azimuth on the face of a scope. This is called a 'B'-Scope presentation. Another type, called 'C'-Scope presentation, plots elevation vertically and azimuth horizontally. 'B'-scopes and 'C'-Scopes are used infrequently and in specialist applications such as mortar locating and aircraft, ground-controlled-approach radars.

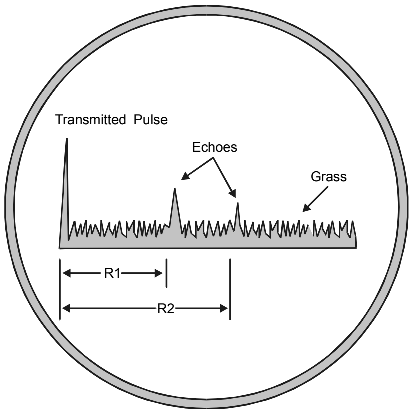


Figure 4: The 'A'-Scope Display

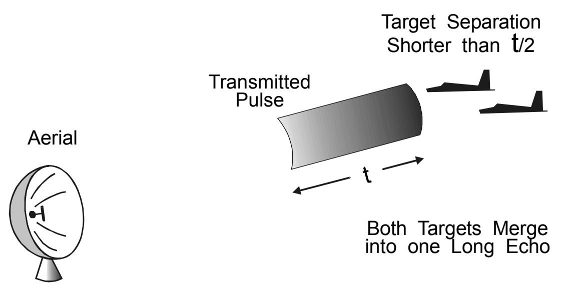


Figure 6: Illustrating Range resolution

PPI: the most common type of radar display is The Plan Position Indicator, or PPI presentation, shown at Figure Five. The display shows a representation of the area around the radar as viewed from above, just like a map. Older radar displays placed the radar at the centre but modern computer-controlled displays can be shifted so that the radar can appear to be anywhere on (or even off) the display. The display indicates the range and bearing to a target but there is no elevation information displayed (unless a computer-controlled display prints the height of a target next to its position on the display).

MINIMUM RANGE OF A RADAR

A pulsed radar cannot begin to receive until the entire outgoing pulse has been transmitted. This is because the antenna is shared between the transmitter and the receiver - but only one device at a time may use it. For a typical pulse duration of 10 µs then this means that no echoes can be received during the first ten micro-seconds of operation. Using the simple rule that each micro-second of radar time corresponds to 150 m of radar range then we reach the conclusion that the minimum range of a radar is 150 m for each micro-second of pulse duration. For our typical radar then the minimum range is 1.5 km and no targets closer than that distance will be detected. In equation form:

$$R_{min} = \tau \times 150 \text{ m.} \quad (\tau \text{ in micro-seconds})$$

In practice, the duplexer might add a few more micro-seconds to this time, as it does not necessarily switch over instantaneously. Consequently, the minimum range will be a little greater than that calculated using only the pulse duration.

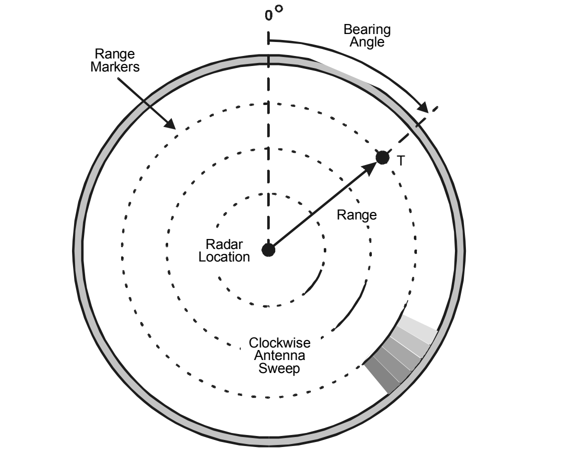


Figure 5: The PPI Display

RANGE RESOLUTION

If a radar has two targets in its beam then for one transmitted pulse there will be two echoes, one from each target. In order to recognise this then the two pulses must arrive with some separation between them, otherwise they will merge into one larger echo. The large echo would be recognised as one larger target and not as two, distinct targets. The ability to distinguish between targets at slightly different ranges is called 'Range Resolution' and this is illustrated in Figure Six.

The separation of the two echoes must be greater than the pulse duration if they are to be seen as two, distinct echoes. In our sample radar, the pulse duration is 10 µs so the two echoes must arrive back with a time difference greater than this. Using the standard rule that each micro-second corresponds to 150 m of range we conclude that the two targets must be more than 1.5 km apart to be recognisably distinct. In equation form:

$$R_{res} = \tau \times 150 \text{ m.} \quad (\tau \text{ in micro-seconds})$$

Example 9: A radar operates with a pulse duration of 2 µs. What is its minium range?

$$R_{min} = \tau \times 150 \text{ m} = 2 \times 150 = 300 \text{ m}$$

Example 10: A radar operates with a pulse duration of 4 µs. What is its range resolution?

$$R_{res} = \tau \times 150 \text{ m} = 4 \times 160 = 600 \text{ m.}$$

A technique called 'Pulse Compression' can be used in the receiver to make the pulse appear to be shorter. This is used to improve the range resolution in radars that use long pulses. This technique is covered in another handout.

NUMBER OF HITS ON A TARGET

As the radar beam sweeps past the azimuth of a target then a stream of pulses will hit the target and produce a stream of echoes. The number of pulses that hit the target is given by the formula:

$$N_{hits} = \frac{PRF \times \theta_b}{360 \times \Omega}$$

where θ_b is the beamwidth of the antenna (in degrees) and Ω is the rotation rate of the antenna (in revolutions per second).

Example 11: A radar operates with a PRF of 10 kHz, a rotation rate of 60 rpm and a beam width of 4°. How many pulses hit a target in each scan?

$$N_{hits} = \frac{PRF \times \theta_b}{360 \times \Omega} = \frac{10\,000 \times 4}{360 \times 1} = 111 \text{ hits}$$

Note: 60 revs per minute is 1 revolution per second!

MAXIMUM RANGE OF A SIMPLE RADAR

The maximum range of a radar is reached when the strength of the echo from a potential target is too weak to be detected by the radar. To some extent, the maximum range in practice will depend on the type of targets that the radar is trying to detect. A commercial airliner (large surface area, without any stealthy features, flying high) will be detectable at a much greater range than a small fighter aeroplane (small area, stealthy features, terrain-following flight-profile).

An indication of the maximum useable range of a simple radar could be obtained from its pulse interval. The radar 'clock' starts when a pulse is transmitted and is re-set when the next pulse is transmitted (after one pulse interval). During this 'listening time' the radar tries to detect echoes. Consequently, any echoes that arrive after that time are not counted. This range is usually called the 'Instrumented Range' of the radar.

As always, each micro-second of time corresponds to 150 m of range so, each micro-second of pulse interval corresponds to 150 m of instrumented range. For example, a simple radar with a pulse interval of 100 µs is expecting targets at ranges up to 100 × 150 m or 15 km. In formula terms:

$$R_{max} = T \times 150 \text{ m.} \quad (\text{'T' in micro-seconds})$$

RANGE AMBIGUITY

If a radar were to transmit just one pulse and then wait for an echo then there would little doubt that the echo came from that pulse. Even the Moon, about 400 000 km away from the Earth, will give an echo eventually, provided that the antenna does not turn to another direction during the two seconds, or so, that the echo would take to return.

Pulsed radars actually transmit a continuous stream of pulses and receive, hopefully, a continuous stream of echoes from a target. Since all the pulses are identical then the radar cannot identify which echo came from which pulse and this gives rise to an ambiguity in the range measurement.

The problem of range ambiguity is illustrated in Figure Seven. The Figure shows a series of radar transmissions (pulses numbered 547, 548, etc.) and a series of echoes (labeled 'a', 'b', etc.). The pulse interval is 100 µs and an echo arrives 50 µs after each pulse was transmitted. The problem is in deciding which echo came from which pulse. The following options are possible and equally likely:

- Echo 'a' belongs with pulse '547' and the target is a small fighter at a range of 7.5 km. (50 µs radar time delay).
- Echo 'b' belongs with pulse '547' and the target is a small bomber at a range of 22.5 km (150 µs radar time delay). Echo 'a' came from pulse 546.
- Echo 'c' belongs with pulse '547' and the target is a jumbo jet at a range of 37.5 km (250 µs radar time delay). Echo 'a' came from pulse '545' and Echo 'b' came from pulse '546'.

In each case, the increase in range (which would tend to reduce the signal strength in the echo) was balanced by an increase in target size (which would tend to increase the strength of the echo). In practice, this radar cannot know for certain the range of the target. It could equally well be 7.5 km, 22.5 km or 37.5 km - the radar does not have sufficient data to decide which range is the correct one. This range ambiguity occurs in all pulsed radars and the radar designer must provide a means of resolving it (the solutions to this problem are described later on in this handout). The amount of range ambiguity is equal to the instrumented range of the radar (T × 150 m).

The possible ranges include the apparent range (in this case 7.5 km - because the echo arrives 50 µs after the most recently transmitted pulse) plus any whole number times the 'maximum simple range' (in this case 15 km). Although the above example was stopped at 37.5 km, the list of possible ranges goes on for ever. The radar in its present state cannot identify which range is correct. In formula terms:

$$R = \text{Apparent 'R'} + n \times R_{max}$$

where 'n' is a whole number (e.g. 1, 2, 3, etc.)

Echoes that return from targets beyond the simple maximum range are called 'second-trace echoes' because, on the old 'A'-scopes they would appear on the display on its second trace rather than on its first trace. They would have arrived back too late to show on the first trace.

The strength of the echo cannot reliably be used as an indicator of range because the target might have stealthy features that cause it to give only a small echo, even when close to the radar.

Additionally, a target that is at a range equal to the maximum range of the radar would give an echo that returned just as the next pulse was being transmitted. This echo would not be received because the receiver is switched off during transmission of the pulse. A manœuvring target being observed by the radar would vanish from the screen when it reached that range. This 'Blind Range' is equal to the instrumented range of the radar and any multiple of that range.

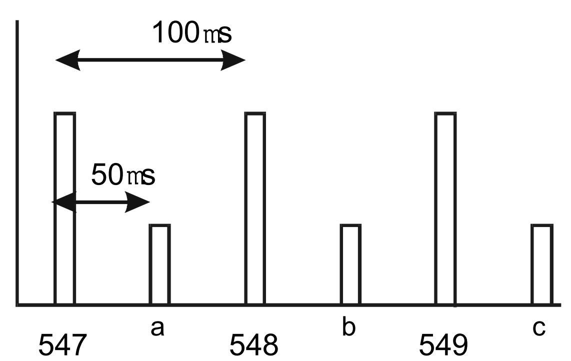


Figure 7: Radar Pulses and Echoes

Example 12: A radar operates with a pulse interval of 120 µs. A target appears at an apparent range of 10 km - at what other ranges might the target be located?

R_{max} = T × 150 m = 120 × 150 = 18 km. This represents the instrumented range and the amount of range ambiguity.

The target might be at its apparent range plus any number times the instrumented range: 28 km (10 + 18), 46 km (10 + 36), 64 km (10 + 54), etc. The radar cannot know which is correct.

Example 13: A radar operates with a pulse interval of 100 µs and detects a target at an apparent range of 13 km. What are the other possible ranges of this target?

R_{max} = T × 150 m = 100 × 150 = 15 km. This represents the instrumented range and the amount of range ambiguity.

The other possible ranges are: 28 km (13 + 15), 43 km (13 + 30), 58 km (13 + 45), etc. The radar cannot know which is correct.

RESOLVING RANGE AMBIGUITY - MULTIPLE PRFS

One simple way to resolve range ambiguity is for the radar system to switch to a different pulse repetition frequency (PRF). Since the amount of range ambiguity depends on the PRF then it will change when the PRF is changed. Since the pulse interval ('T') is equal to 1/PRF then changing the PRF is the same as using a different pulse interval.

Referring back to Examples Twelve and Thirteen: a radar system with a pulse interval of 120 µs has a PRF of 8.333 kHz, the radar with a pulse interval of 100 µs has a PRF of 10 kHz. If this radar were to switch from one PRf to the other PRF every few dozen pulses, whilst it continued to scan a target, then echoes from that target would be received from both PRFs.

The first PRF indicates a range of 10, 28, 46, or 64 km whereas the second PRF indicates a range of 13, 28, 43, or 58 km. Clearly, if this is just one target then it can only be at one range - the one that appears in both lists. Therefore the true range of this target is 28 km, because it appears in both lists of possible ranges. The radar has to perform a process called 'Correlation' to verify that the two sets of echoes actually belong to the same target.

For many radar systems then only the first two or three possible ranges in each list need be considered. This is because any echoes that come from targets at greater distances than that would probably be too weak to register on the radar.

Switching PRFs gives the additional advantage of uncovering targets that are at the blind range for one of the PRFs. Such targets would be invisible at one PRF but clearly visible at the other. Targets at the instrumented range are always invisible to a pulsed radar because their echoes always arrive back at the radar whilst the next pulse is being transmitted. The duplexer would have disconnected the receiver from the antenna so that the transmitter could use it so any echo would never reach the receiver. Even if any echo signal were to reach the receiver then the echo would be so small in relation to the transmitter's output that it would be completely masked by it.

Yet another advantage of switching PRFs is that it makes it more difficult for an enemy to jam the radar by spoofing its signals. The enemy's jamming must try to keep up with the radar's constant changes of PRF and carrier frequency - this takes some time to accomplish as his jamming equipment must search for the new settings and lock onto them before attempting to send back false echo signals.

Rapier FSB2 does not actually use PRF switching to solve the range ambiguity problem. This is covered in another handout. Rapier FSC switches PRF and carrier frequency every eight pulses - if the echo from the first pulse appears to be missing then that can indicate a target that is beyond the instrumented range as this echo would return after pulse two has been transmitted. The late echo from the eighth pulse of the previous group would not be received as the receiver would have already changed to the new frequency for the next group.

Example 14: A radar operates with a pulse interval of 200 µs. A target appears at an apparent range of 10 km. When the Pulse Interval is changed to 180 µs then the same target appears at an apparent range of 13 km. At what other ranges is the target actually located?

First PI: R_{max} = T × 150 m = 200 × 150 =30 km.
This represents the amount of range ambiguity, so the target might be at its apparent range plus any number times 30 km: 10 km, 40 km, 70 km, etc. Only one can be correct but we can't tell.

Second PI: R_{max} = T × 150 m = 180 × 150 = 27 km. This represents the amount of range ambiguity. The possible ranges are: 13 km, 40 km, 67 km, etc. As before, only one can be correct.

Solution: which range appears in both lists? The range of 40 km. That must be the true range of the target.

DETERMINING AZIMUTH

Although the radar antenna might be pointing in a particular direction (e.g. a bearing of 045°) the beam of radiated EM-waves spreads by a few degrees either side of that direction. Thus, an echo received whilst a typical radar antenna is pointing 045° could have come from a bearing of anywhere between 043° and 047°.

The beamwidth is defined as the angle between the points where the power has fallen to half the power in the centre of the beam. Thus, even at the 'edge' of the beam, the power is not zero. Nevertheless, that point is taken as the edge of the beam. The beamwidth represents the basic accuracy of angular measurements that the radar can make.

If the radar antenna is rotating then the bearing of the target can be estimated more accurately than the beamwidth. This is because the strength of the radar echo will rise and fall as the beam sweeps past the target. The angle that gives the greatest echo can be assumed to be the correct direction to the target because the target is then in the centre of the beam.

In a previous paragraph, you saw that a radar might be able to ‘hit’ a target with about one hundred pulses during each scan of the antenna. The radar receiver can observe the variation in echo strength during those hundred hits and use the rise and fall of signal strength to find a more precise bearing to the target. In principle, with one hundred hits on the target, the radar could measure azimuth to within one-hundredth of its beam width. Since the beamwidth might be only a few degrees then this ability to use the variation in signal strength as the beam sweeps through the target’s azimuth can allow a very accurate measurement of azimuth. This variation is illustrated in Figure Eight, although the Figure shows far less than one hundred radar echoes in order to keep the diagram simple.

EFFECT OF NOISE ON THE RADAR

Noise is essentially random in nature, but it obeys some statistical laws. For example, it will have an average value but there might be a 30% chance that the noise would be twice as great as the average, a 5% chance that it is three times greater and a reducing - but not zero - chance that it could be much greater than the average. Since a large amount of noise could be mistaken for an echo then a radar needs some means of distinguishing between the two in order to avoid false alarms. Furthermore, some jamming techniques attempt to insert extra noise into a radar receiver in order to impair its operation.

One important difference between the echo from a target and the noise is that the echo is much more consistent and regular. If we considered one radar pulse and its echo then it would be difficult to distinguish the echo from the noise. However, if we considered fifty pulses and fifty echoes then it is unlikely that random noise would appear consistently, at the right moment, fifty times, to give a false target. Whereas, we would expect to get fifty consistent echoes from a real target. In effect, observing the target for a longer period of time (e.g. during 100 pulses) causes the noise to be averaged and this gives a smaller value than the average of the echo signal because the echo is consistent.

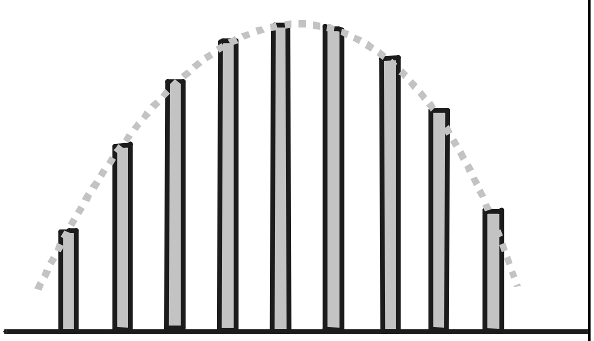


Figure 8: Variation in Signal Strength as the Radar Scans though the Target’s Azimuth

The noise differs from the echo in other ways (e.g. no Doppler Shift) and radar receivers use a variety of techniques to exploit these differences to extract a useful echo signal from a lot of noise.

Many radar receivers monitor the noise frequently and use the amount of noise to determine a ‘threshold’ value. Only signals above the threshold are recognised as targets. As the noise level changes then the threshold is changed to match and this gives the radar a constant, false-alarm rate (C-FAR).

When noise is significant then echo pulses do not have a nice sharp edge that can be used to determine their precise start and end points. This causes a decrease in the accuracy of range measurements since the radar receiver cannot easily measure the time of arrival of the pulse. Noise also causes inaccuracies in bearing measurement because it masks the rise and fall of echo strength as the antenna scans across the bearing to a target.

The principal factor that determines the detectability of a radar echo is the amount of energy in each pulse. This is calculated by multiplying the power during the pulse (e.g. 3 kW) by the duration of the pulse (e.g. 10 μs) to get the energy (e.g. 30 mW). This is one reason why a radar would use long pulses - to get more energy into each pulse and, hence, to increase detectability of targets.

CONTINUOUS WAVE (CW) RADAR

Pulsed radars use pulses primarily to measure range. If range is not required, or can be found in some other way, then the radar need not use pulses - it could transmit continuously. Such a radar is called a Continuous Wave (CW) Radar. The CW radar would be used where range was not important or not measured by timing a radar pulse.

The CW radar has a duty cycle of 100% so its peak power is the same as its average power. In the example that we used for pulsed radar, the peak power was 3 kW with a duty cycle of 10% and that gave an average power of 300 W. A CW radar could achieve the same effect with a steady power of 300 W. Consequently, CW radars tend to operate at lower transmitter power than pulsed radars.

Three examples of military CW radars that you might encounter are:

- **Radar Gather Unit (RGU)**: used in Rapier FSC to guide the missile into the line of sight of the tracking radar. This measures the angle between the missile and the boresight of the radar - i.e. how far the missile is from the correct flight line (e.g. 25 mils too high or 36 mils to the left of centre).
- **Muzzle Velocity Measuring Device (MVMD)**: used in AS90 to measure the velocity of each round as it is fired. This just measures the Doppler shift to find the muzzle velocity (e.g. 320 ms^{-1}).
- **Miss-Distance Indicator (MDI)**: used on Banshee and Falconette to measure how closely the missile

HOW MDI WORKS

The MDI Radar is a CW Radar that indicates how closely a missile approaches the target as it flies past. With likely closing speeds in excess of 1 000 ms^{-1} then the missile will not remain at the closest point for very long. To make a direct measurement of the miss-distance would be very difficult indeed.

Pulsed Radar: it would not easy to measure the miss-distance using a pulsed radar as the distance is likely to be only a few metres and this would require a very short pulse (less than 1/150 μs) and accurate measurement. The pulse repetition frequency would also have to be very high in order to ensure that an echo was received as the missile passes through the point of closest approach.

CW Radar: the technique used does not rely on making a measurement only at the point of closest approach. Instead, the variation in Doppler shift is measured as the missile approaches, passes and recedes. The Doppler shift depends on the radial velocity of the missile and this, in turn, depends on the angle between the track of the missile and the line-of-sight from the target.

Close Approach: if the missile is going to pass very close to the target (e.g. 1 m) then for much of the approach the missile is almost head-on. The radial velocity is almost the same as its actual velocity, because the angle between the track and the line-of-sight is very small. Only when the missile gets very close to the target will the Doppler shift change. Imagine that you were watching this missile, from the target - your head would face in the same direction until the missile was very close then, suddenly, you would have to turn your head to follow the crossing missile. The angle through which you turn your head to follow the missile is the 'Θ' in the equation:

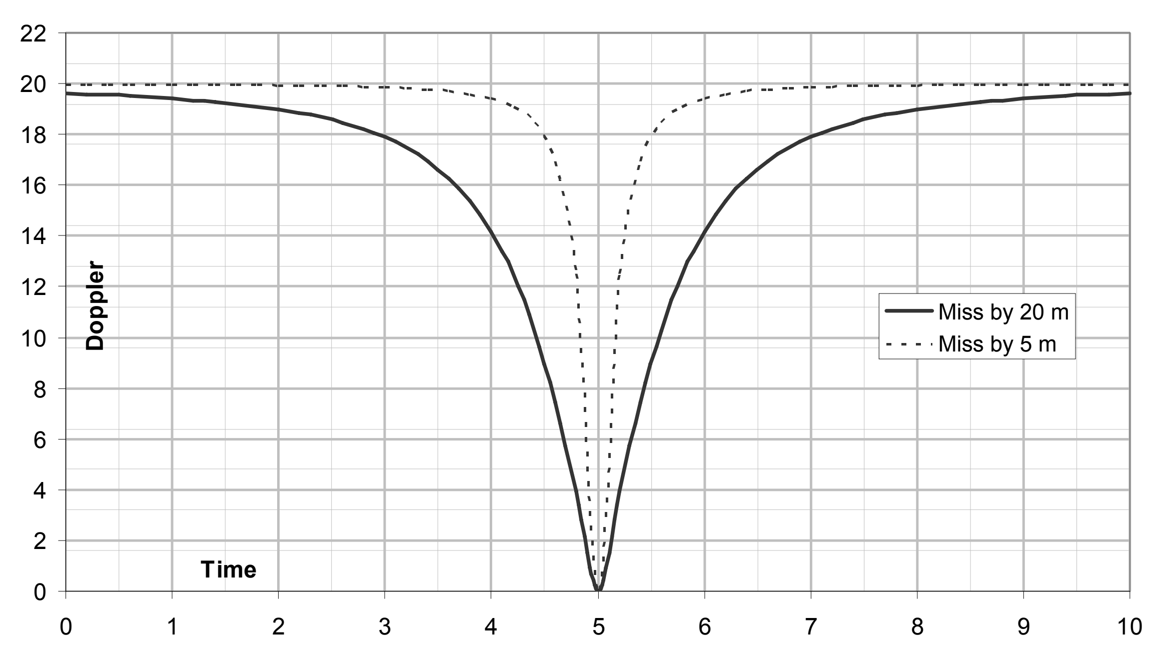
$$V_r = V \times \cos \Theta$$

that relates radial velocity (V_r) to actual velocity (V) and it is the radial velocity that causes the Doppler shift. Consequently, the Doppler shift does not alter until the missile is very close.

Miss by a large amount: is the missile is going to miss by a large amount then the approach is not head-on at all. If you were watching this missile from the target then your head would be turning steadily, as the missile crosses the sky. Even when it was some distance away then your head would have turned to follow it. This turning means that there is a large angle between the track of the missile and the line-of-sight and, consequently, the amount of Doppler shift is reduced whilst the missile is further away and the curve, below, is much wider..

Graphs: The graphs, below, show idealised Doppler shifts for two missiles. One is going to miss by 5 m and the other by 20 m. The miss distance affects the area of the 'dip' in the curve. The narrower the dip then the closer was the approach. The MDI instrument plots a graph of the amount of Doppler shift, ignoring the fact that it is added to the signal during the approach phase and subtracted from the signal during the recede phase. Having obtained this plot, then the software calculates the area enclosed by the dip in the graph and, from this figure, estimates the miss-distance.

In practice, the line is not as sharp as that shown in the Figure. The line is broad and fuzzy due to the effects of noise on the received signals. The largest contribution to the area within the curve occurs at, or near, the zero point (since this is where the dip is greatest. At this point, the missile is at its closest point to the MDI and, consequently, the radar echo is strongest so the noise is less of a problem.



approached the target. Although this measures a sort of range it does not measure it directly - it uses the changes in Doppler shift as the missile passes. (See the side bar on previous page for a technical description of MDI).

BLOCK DIAGRAM OF CW RADAR

The distinctive feature of the CW radar is the presence of two antennae: one for the transmitter and the other for the receiver. In a pulsed radar, the transmitter and receiver operate alternately so the antenna could be shared between them. A CW radar transmits continuously and requires a separate antenna for the receiver. To reduce any leakage of the transmitted signal directly into the receiver's antenna there is often a barrier of some sort placed between the two antennae.

The various components of a typical CW radar are shown in Figure Nine. The function of each component is as follows:

- **CW Transmitter**: this produces the outgoing signal, perhaps under computer control. The output is often a steady sine-wave of constant frequency and amplitude. Some systems add a binary code to the outgoing signal so that the echoes can be identified as having come from the radar. Typical power output might be between ten and one hundred times lower than a pulsed radar.
- **Antennae**: CW radars require two antenna and some means of preventing signals' taking the direct route from the transmitting antenna to the receiving antenna. This is indicated in the Figure by the 'barrier', which is usually made of a material that absorbs radar waves (e.g. plastic material with added carbon)

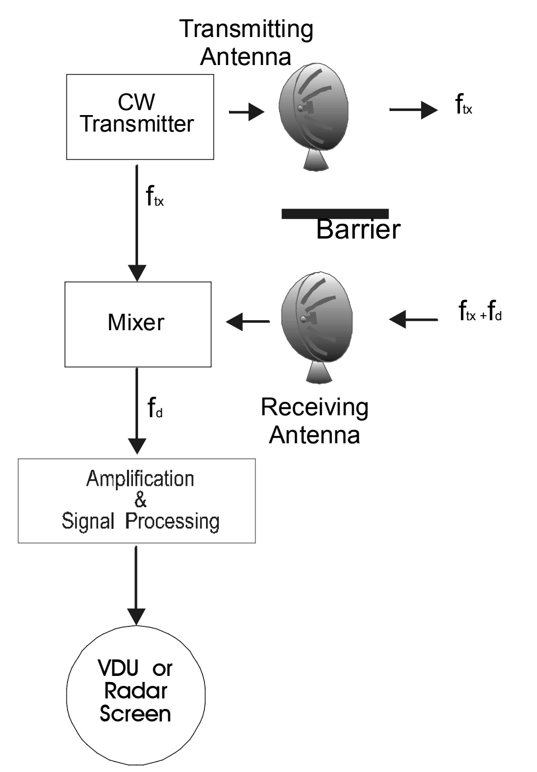


Figure 9: Block Diagram of a CW Radar

- **Mixer**: this is the first part of the receiver where the echo signal is mixed with the original signal, sent at low-power from the transmitter. The mixer extracts information about the strength and phase of the echo and any Doppler shift. It is broadly similar to the mixers used in pulsed radar except that it operates with a continuous signal. The output from the mixer is usually at a much lower frequency than the transmitted signal, as these lower frequencies are much easier to process that the higher ones. (High frequencies are used in radar because their wavelength is small so they can be used to give obtain more detailed information and they also require smaller antennae.)
- **Amplification & Signal Processing**: this part of the radar amplifies the signal and analyses its content. In a modern radar then this will operate under the control of the computer.
- **VDU or Radar Screen**: the operator's display (if there is one) for displaying information derived from the radar signals.

SUMMARY OF FORMULAE

Range and time

each micro-second, of round-trip time, represents 150 metres of radar range.

or

$$R = \frac{c \times t_d}{2}$$ (t_d is the delay time)

Number of radar cycles in each pulse

$$n = \text{Pulse Duration} \times \text{Radar Frequency}$$

Duty Cycle

$$DC\% = \frac{\text{Time On}}{\text{Total Time}} \times 100\ \%$$

$$DC\% = \frac{\text{Pulse Duration}}{\text{Pulse Interval}} \times 100\ \%$$

$$\text{Mean Power} = \text{Duty Cycle} \times \text{Peak Power}$$

Pulse Interval and PRF

$$PRF = \frac{1}{\text{Pulse Interval}}\ \text{Hz}$$

$$\text{Pulse Interval} = \frac{1}{PRF}\ \text{seconds}$$

Minimum Range

$$R_{min} = \tau \times 150\ \text{m.}$$ (τ is the pulse duration, in micro-seconds)

Range Ambiguity (Maximum Range)

$$R_{max} = T \times 150\ \text{m.}$$ ('T' is the pulse interval, in micro-seconds)

Pulse Energy

$$E_p = \tau \times \text{Peak Power}$$

SELF-TEST QUESTIONS

1. An echo from a target is received after a delay of 4.5 µs. The range of the target is.

a. 1,350 m.
b. 338 m.
c. 675 m.
d. 4,800 m.

2. A target is at a range of 6.75 km. The echo from this target will reach the receiver after a delay of:

a. 4.5 µs.
b. 22.5 µs.
c. 45 ms.
d. 45 µs.

3. A radar has a pulse duration of 8 µs and a pulse interval of 400 µs. The Duty Cycle, of this radar is:

a. 20 %.
b. 2 %.
c. 20 %.
d. 0.2 %.

4. A radar has a peak power of 4 kW and a Duty Cycle of 5 % The Mean Power of this radar is:

a. 2 W.
b. 20 W.
c. 200 W.
d. 2,000 W .

5. A radar with a PRF of 10 kHz has a pulse interval of:

a. 10 ms.
b. 10 µs.
c. 100 µs.
d. 1 µs.

6. A radar with a pulse interval of 200 µs has a PRF of:

a. 5 kHz.
b. 20 kHz.
c. 2 kHz.
d. 50 kHz.

7. In a pulsed radar, the duplexer enables the use of:

a. short pulses from the transmitter.
b. antenna sharing between transmitter and receiver.
c. long pulses from the receiver.
d. accurate timing of signals.

8. A radar uses a pulse length of 8 µs and transmits at a frequency of 5 GHz. The number of cycles of radar wave in each pulse is:

a. 40,000.
b. 4,000.
c. 400.
d. 40.

9. When the echo signal of a radar is weak, compared to the noise, then the signal can often be distinguished from the noise because the signal:

a. appears at random places on the display.
b. appears in a consistent place on the display.
c. is much smaller than the noise.
d. has a Doppler shift.

10. A radar that uses a pulse duration of 6 µs will have a minimum range of:

a. 1,800 m.
b. 900 m.
c. 600 m.
d. 360 m.

11. A radar that uses a pulse duration of 5 µs has a range resolution of:

a. 50 m.
b. 250 m.
c. 750 m.
d. 1,500 m.

12. A radar operates with a beam width of 3°, a PRF of 6 kHz and a rotation rate of 2 revolutions per second. The number of hits on a target during each scan will be:

a. 25.
b. 36.
c. 100.
d. 360.

13. A radar that operates with a PRF of 12 kHz has a simple maximum range of:

a. 12 km.
b. 1.2 km.
c. 24 km.
d. 18 km.

SELF-TEST QUESTIONS

14. A radar uses a PRF of 5 kHz and echoes from a target are received 40 µs after each transmitted pulse. Allowing for range ambiguity, two possible ranges to the target are:

   a. 6 km or 10 km.
   b. 12 km or 36 km.
   c. 5 km or 45 km.
   d. 6 km or 36 km.

15. When a radar has a simple maximum range of 12 km then a target at a true range of 18 km might appear to be at a range of:

   a. 6 km.
   b. 12 km.
   c. 24 km.
   d. 36 km.

16. A radar that uses a PRF of 10 kHz has a range ambiguity of:

   a. 150 m.
   b. 10 km.
   c. 15 km.
   d. 25 km.

17. A surveillance radar, with a beam width of 5°, that hits the target with 50 pulses during each scan could, under ideal conditions, measure azimuth to an accuracy of approximately:

   a. 5°
   b. 10°
   c. 1°
   d. 0.1°

18. When the level of noise rises in the receiver of a CFAR radar then the system could react by increasing the:

   a. operating frequency.
   b. PRF.
   c. wavelength.
   d. detection threshold.

19. When the level of noise rises in any radar receiver then the likely result is a decrease in:

   a. measurement accuracy.
   b. minimum range.
   c. PRF.
   d. detection threshold.

20. One difference between a CW radar and a pulsed radar is that the CW radar has:

   a. separate transmit and receive antennae.
   b. higher operating power.
   c. higher PRF
   d. good range resolution.

Answers

1. c = 150 m for each micro-second
2. d = 6,750 ÷ 150
3. b = 8 ÷ 400 × 100%
4. b = 4,000 × 5%
5. c = 1 ÷ 10,000
6. a = 1 ÷ 200 µs
7. b = duplexer allows one antenna to do two jobs.
8. a = 8 µs × 5 GHz
9. b = noise at random, signal consistent.
10. b = 150 m for each µs
11. c = 150 m for each µs
12. a = (3 × 6,000) ÷ (360 × 2)
13. d = 150 m for each µs
14. b = Pulse Interval = 200 µs -> 30 km ambiguity.
15. a = 18 km - 12 km (ambiguity)
16. c = Pulse Interval = 100 µs -> 15 km ambiguity
17. d = Beam Width ÷ No of hits
18. d = CFAR radars raise threshold when it's noisy.
19. a = noise decreases accuracy.
20. a = CW radars need two antennae.

Teaching Objectives		Comments
H.01.01 Describe the production of radar echoes		
H.01.01.01	State that radar energy propagates away from the radar in the form of EM waves.	
H.01.01.02	Describe the process of scattering of EM energy by a target.	Scattering from any region that is different from it surroundings.
H.01.01.03	Describe the process of specular reflection of EM energy by a target.	Reflections from smooth metallic surfaces and shapes.
H.01.01.04	State that the received signal is very small and decreases with increasing range.	
H.01.01.05	State that the echo will have a Doppler shift dependent on its radial velocity.	Doppler Shift, $f_d = 2v_r/\lambda$
H.01.01.06	State that the echo will be delayed in time.	Delay, $t_d = 2R/c$, use of 150 m per μs.
H.01.02 Describe the operation of a simple CW radar		
H.01.02.01	State that a continuous wave (CW) radar emits EM energy continuously and that the duty cycle is 100%.	
H.01.02.02	Recognise the components of a block diagram of a CW radar and describe their basic function.	
H.01.02.03	State that a CW radar requires separate receive and transmit antennae.	
H.01.02.04	State that a CW radar has no range information.	
H.01.02.05	State that a CW radar can determine the direction of the target by using a directional antenna.	Might include both azimuth and elevation.
H.01.02.06	State that a CW radar can determine the radial velocity of the target using its Doppler shift.	
H.01.02.07	Describe military applications of CW radar.	MVMD, Radar gather unit of FSC, Miss-distance indicator.
H.01.03 Describe the operation of a simple pulse radar		
H.01.03.01	State that a pulsed radar emits EM energy in pulses of duration ‘τ‘ seconds at intervals of 'T' seconds.	Pulse duration ‘τ‘ and pulse interval ‘T’.
H.01.03.02	Convert between pulse interval ‘T’ and pulse repetition frequency ‘f_r’	PRF, $f_r = 1/T$
H.01.03.03	State that a pulsed radar can determine the range and direction of the target.	May include both azimuth and elevation.
H.01.03.04	Use the relationship $R = ct_d/2$ to link range and time delay.	Where t_d is the time delay of the echo.
H.01.03.05	Recognise the components of a block diagram of a Pulsed Radar and describe their basic function.	
H.01.03.06	Calculate duty cycle and mean power for a pulsed radar.	
H.01.03.07	Identify, on a diagram of an ‘A’-scope presentation, the transmitted and received pulse and calculate the range.	Assume unambiguous target.
H.01.03.08	Recognise the features of, and information displayed on, a plan position indicator (PPI).	
H.01.03.09	Describe the features of, and information displayed on, a computer-controlled, radar display.	

Teaching Objectives		Comments
H.01.04 Describe the factors affecting the minimum range of a pulsed radar		
H.01.04.01	State that the radar cannot receive until the transmitted pulse has ended and that the minimum range will be $c\tau/2$.	E.g. 5 ms gives ¾ km min range.
H.01.04.02	State that there might be an additional factor caused by any delay in the operation of the duplexer and the recovery of the receiver.	Normally very small compared to the preceding.
H.01.05 Describe the factors affecting the range resolution of a pulsed radar.		
H.01.05.01	State that the range resolution is a measure of the ability of the radar to distinguish between targets at different ranges when both targets are illuminated simultaneously.	
H.01.05.02	State that the basic range resolution is $c\tau/2$.	
H.01.05.03	State that when pulse-compression is used then the range resolution is improved by the amount of compression.	Pulse duration is reduced by 'compression' – details to be covered later.
H.01.06 Describe the causes and resolution of range ambiguities in a pulsed radar system.		
H.01.06.01	Describe how range ambiguities arise.	
H.01.06.02	State that all targets are ambiguous.	The radar cannot 'know' which targets are not ambiguous – all targets are!
H.01.06.03	State that a target's range might be the apparent range plus any integer multiple of $cT/2$.	
H.01.06.04	Describe how scheduled changes in the prf are used to resolve range ambiguities.	
H.01.07 Describe the effects of scanning the beam across the target.		
H.01.07.01	State that scanning is used to determine the direction of the target.	Either azimuth or elevation – azimuth preferred for example – surveillance radar.
H.01.07.02	Relate beamwidth, θ_b, scan rate, Ω, and f_r to the number of target hits per scan using: Hits = $(\theta_b\ f_r)\ /\ (360\Omega)$.	θ_b = Beam Width, f_r = prf, Ω = scan rate in revs per second (rpm ÷ 60)
H.01.07.03	Describe the variation in echo signal as the beam is scanned through the target.	Stationary target.
H.01.07.04	State that the angular resolution may be narrower than the beamwidth if this variation is taken into account.	
H.01.08 Describe the effects of noise on a pulsed radar		
H.01.08.01	State that the noise power might be comparable in size to the echo from a single pulse.	
H.01.08.02	State that the noise can be reduced by signal processing.	To be covered later.
H.01.08.03	State that noise can mask targets that are near the threshold.	
H.01.08.04	State that noise can be mistaken for a target.	
H.01.08.05	Describe the effects of noise on range accuracy.	Signal crosses threshold earlier or later dependent on the random noise value.
H.01.08.06	Describe the effects of noise on angular accuracy.	Changes variations due to antenna angle at random – the max might not occur at the centre of the beam.
H.01.08.07	State that the energy in a pulse is the principal factor determining the detectability of the echo.	Energy = Power × Time