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RADIO NAVIGATION

CHAPTER 9 – BASIC RADAR PRINCIPLES AND GROUND RADAR

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CHAPTER 9: BASIC RADAR PRINCIPLES AND GROUND RADAR

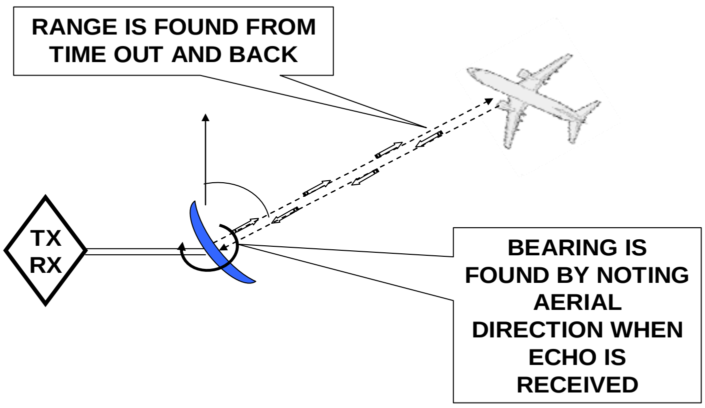
WHAT IS "RADAR"?

The term RADAR came from the phrase “Radio Detection and Ranging “and although the uses of radar are much greater than original considered, the term has remained in use.

RANGE AND BEARING BY PULSE TECHNIQUE

The range of an object from the radar site can be found by measuring the time a pulse of radio energy takes to travel to the object and back again. Radio energy travels at a speed of approximately 300 X 10^6 metres per second or 300 metres per micro-second (μsec).

Bearing can be measured by noting the aerial direction when an echo of the radar pulse is received.



RADAR DEFINITIONS

PULSE LENGTH alternatively known as pulse width is the duration of the pulse in microseconds.

PULSE REPETITION FREQUENCY is the number of pulses transmitted per second. Otherwise known as the Pulse Recurrence Frequency

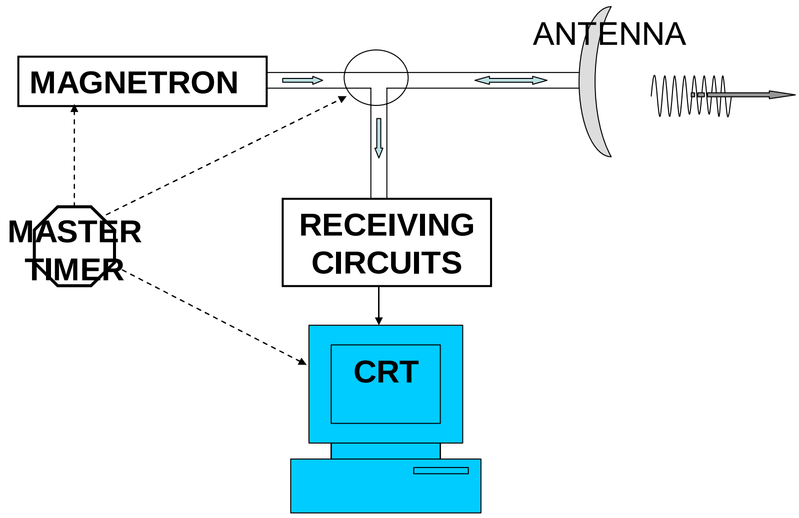
PULSE REPETITION INTERVAL is the time interval from the start of one pulse to the start of the next. The Pulse Repetition (or Recurrence) Interval is the reciprocal of the Pulse Repetition Frequency.

$$PRI = \frac{1}{PRF}$$

BEAM WIDTH describes the angular dimension of the radiation pattern. Most radars make use of aerials that concentrate the energy into a narrow beam.

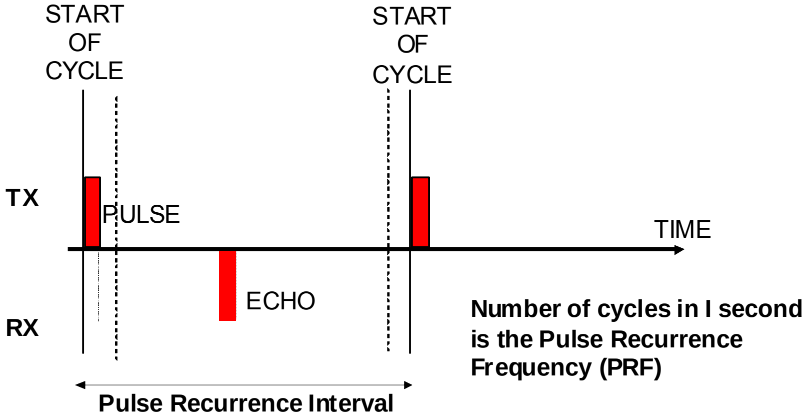
BASIC RADAR SYSTEM

For a very brief period of time, usually between 2 and 30 millionths of a second, the transmitter is radiating high frequency energy. This series of pulses of radar energy is delivered to the antenna. It is common for the same antenna to be used to receive the echoes of the pulses but became the receiver has to be very sensitive, it must be protected when high power pulses are being transmitted. This is achieved by the transmit-receive (T/R) switch which isolates the receiver when transmissions are occurring. The coordination between the Magnetron (transmitter unit), the T/R switch and the CRT (Display) is carried out by the Master Timer. The Receiving Circuits amplify the weak returning echoes.



THE RADAR CYCLE

Each cycle of the radar starts with a pulse of energy leaving the transmitter for a duration of a few microseconds. Even though this is a very short period of time, the pulse will contain many thousands of cycles of the radio frequency. Furthermore the radar pulse has a physical dimension of hundreds of meters. That is the leading edge of the pulse is already distant from the transmitter when it is switched off. After the pulse, the T/R switch operates and a recovery period allows the antenna and receiver to be ready for the echo of the pulse which will then return. The echo from the target can be received during the listening period which ends when the T/R switch prepares the antenna to handle the pulse at the beginning of the next cycle.



It should be noted that the duration of the pulse (pulse length) is very short compared with the Pulse Recurrence Interval. For most of the time, the radar is listening for echoes of its own transmissions.

THE EFFECT OF POWER ON MAXIMUM RANGE

The maximum range of a radar is dependent on many factors such as the size of the target, the characteristics of the antenna and the receiver gain (amplification). The transmitted power is spread out over a progressively greater area as it travels away from the transmitter and the power density will be reduced according to the inverse square law. Similarly the small amount of power contained within the echo from the target will be attenuated as it returns, again according to the inverse square law. The result is a reduction of power on return to the antenna proportional to range^4. By transposition it can be shown that:

$$\textbf{MAX RANGE} \propto \sqrt[4]{\textbf{POWER}}$$

It follows that to double the range of a radar would require 16 times the original transmitter power and doubling the power would only increase the range by 19%. [$\sqrt[4]{2} = 1.19$]

EFFECT OF PRF ON MAXIMUM RANGE

The energy received by the radar antenna has traveled twice the distance between the transmitter and the target. This 2-way journey must be completed within the Pulse Recurrence Interval (1/PRF) of the radar.

$$\begin{aligned} \text{Distance} &= \text{Speed x Time} \\ \therefore \quad \text{Max range} &= \text{Speed x } \frac{1}{\text{PRF}} \text{ x } \frac{1}{2} \\ &= \frac{\text{Speed}}{2 \text{ x PRF}} \end{aligned}$$

If PRF is 400 pulses per second and the Speed of Radio Waves is 300 X 10^6 m/sec.

$$\text{Max range} = \frac{300 \text{ x } 10^6}{2 \text{ x } 400} = 375\,000 \text{ m} = 375 \text{ km}$$

Many radars use lower PRF when searching for long range targets and higher PRF for closer targets.

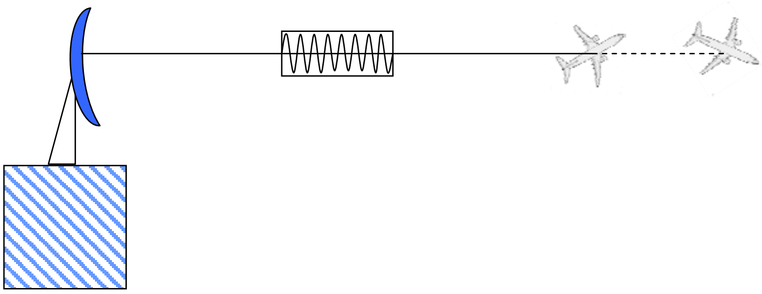
THE EFFECT OF PULSE LENGTH ON MINIMUM RANGE

The minimum range of a radar is determined by the period between the beginning of the transmission of the pulse and the earliest time that the echo can be registered. Ignoring the recovery time, minimum range depends on half pulse length. For example, a weather radar with a pulse length of 2 microseconds would be unable to detect targets closer than 300 metres.

Distance	=	**Speed x Time**
Pulse Length	=	$(300 \times 10^{6}) \times (2 \times 10^{-6})$
	=	600 metres
Minimum range	=	300 metres

THE EFFECT OF PULSE LENGTH ON RANGE RESOLUTION

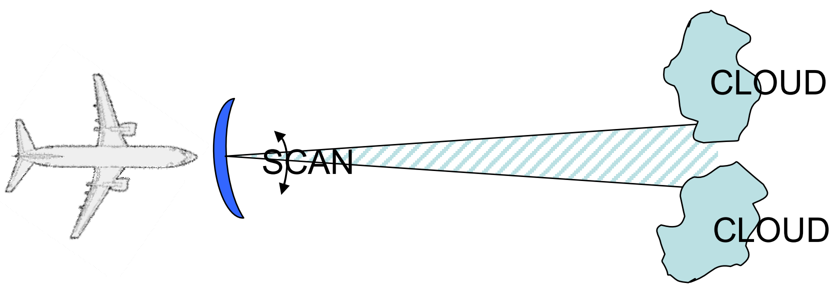
The term 'resolution' refers to the ability of the radar to detect and display close targets separately. In range, resolution is affected by pulse length so that targets that are closer than half pulse length will merge and appear as one. This occurs when the leading edge of the pulse has returned from the further target before the trailing edge of the pulse has returned from the closer target.



TARGETS CLOSER THAN THE EQUIVALENT OF HALF PULSE LENGTH MERGE AND APPEAR AS ONE

THE EFFECT OF BEAM WIDTH ON AZIMUTH RESOLUTION

Azimuth resolution refers to the ability of the radar to separate targets that are at the same range but on different bearings. This depends largely on beam width for if the space between the targets is insufficient, the radar beam will detect the second target before leaving the first.



Beam width depends on antenna characteristics and wavelength and the diameter of the beam increases with range.

Figures from a manufacturer of weather radar are given below:

AERIAL SIZE	BEAM WIDTH	BEAM DIAMETER (nm) AT DIFFERENT RANGES 25 nm	50 nm	100 nm	200 nm
10 inch	9.5^{O}	4	8	16	32
12 inch	7.5^{O}	3	6	12	24
18 inch	5.0^{O}	2	4	8	16

THE EFFECT OF WAVELENGTH ON RADAR ATTENUATION

When radio waves pass through the atmosphere some loss of energy occurs. This may take place as absorption of the energy by gases or by precipitation, or by the blocking or scattering of the energy. If the radar energy is blocked by heavy precipitation, for example, targets at greater range may be masked. These effects are dependent on wavelength.

The choice of wavelength depends on the purpose of the radar. A radar with long wavelength would have transmissions unaffected by cloud and precipitation and this would be undesirable for equipment designed to detect storms. On the other hand, long wavelength would be desirable for ATC radar where the masking effect of rain echoes could prevent the detection of aircraft.

Rule: Shorter Wavelength results in Greater Radar Attenuation

WAVELENGTH	ATTENUATION
≥10cm	Negligible Attenuation
3cm	Significant Attenuation in Rain or Cb droplets
1cm	Increasing Attenuation in all types of precipitation and cloud
≤.5cm	Attenuation may be caused by Oxygen, Water Vapour and other gases, as well as by precipitation and clouds.

PRIMARY AND SECONDARY RADAR

Primary radar relies on reflected energy, that is echoes of its own transmissions

EXAMPLES: Airborne Weather Radar (AWR)
Radar Altimeter
Precision Approach Radar (PAR)
Primary Surveillance Radar

Secondary radar relies on the target's reply to the received transmission. The reply requires a second transmitter, normally operating on a different frequency. By using different frequencies for interrogations and replies, the receiver can be tuned to a different frequency to its associated transmitter. The result is that the receiver is not affected by primary echoes so eliminating ground and weather clutter.

EXAMPLES Distance Measuring Equipment (DME)
Secondary Surveillance Radar (SSR)
Traffic Collision Avoidance System (TCAS)

Advantage of Primary Radar:

It is self-contained and does not require the cooperation of the target.

Advantages of Secondary Radar:

Lower power is required for a given range.

Smaller aerials can be used.

Only target replies are accepted so ground and weather echoes are eliminated.

The strength of reply does not depend on the reflection properties of the target.

The replies can be coded to convey information.

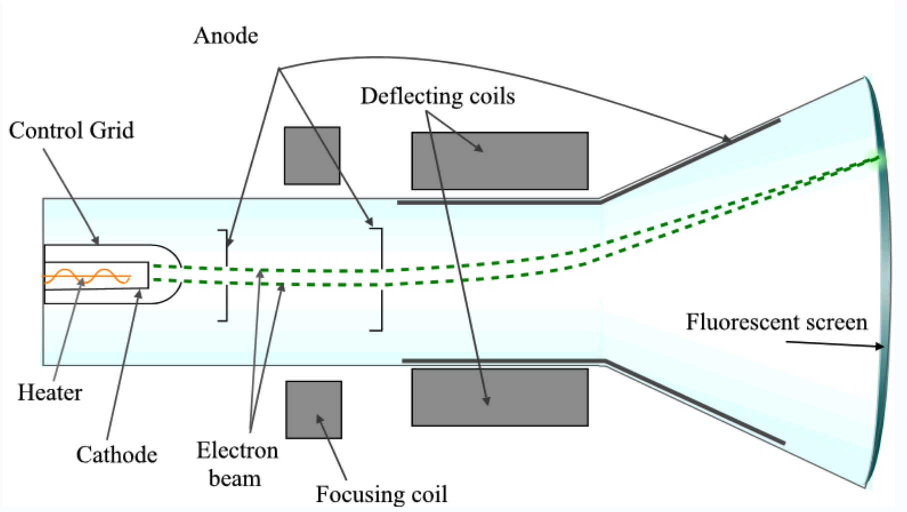
CONTINUOUS WAVE RADAR

The Basic Radar System described earlier in these notes makes use of pulses of energy. This type of radar is the most common but in other types the transmission and reception of energy occur continuously. Continuous wave radar can be used to measure either range or speed. Range measurement, as in pulse radar, is obtained by noting the time taken for energy to travel out and back. The transmitted signal is frequency-modulated so that by the time the energy returns, the transmitter frequency has moved on in its cycle. The difference between the transmitted frequency and the frequency received is a measure of the time taken by the signal to travel out and back. This time period, with a knowledge of the speed of radio waves, allows measurement of range. This principle is used to advantage in modern radio altimeters which, unlike pulse radars, have no minimum range. In CAT III operations the input from the radio altimeter permits approach guidance to zero feet.

Speed can be measured from the Doppler effect. In this case the transmitted signal may be unmodulated and the difference between the transmitted and received frequencies is the result of relative motion between the transmitter and reflecting surface.

THE CATHODE RAY TUBE (CRT)

Advances in airborne radars, such as digital processing, have led to greatly improved colour displays. The following notes describe the CRT which can be used to display signals that have been processed on a digital basis. When digitally processed, returning radar signals are converted to binary which may be stored, retrieved, added or subtracted as on a computer.



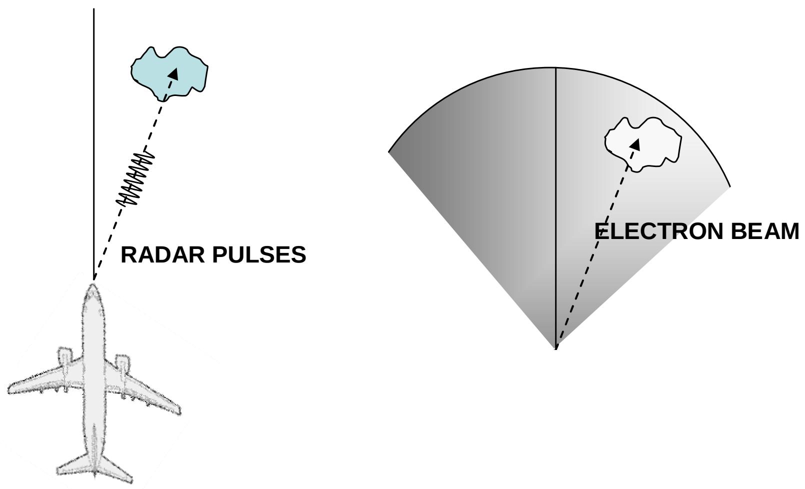
The purpose and function of the main components of the CRT are as follows:

CATHODE	The cathode is the source of the beam of electrons which are negatively charged particles.
GRID	The grid is negatively charged with respect to the cathode. By varying the voltage applied to the grid it is possible to increase the brightness of the spot on the screen created by the electron beam or to cut off the beam so that the spot does not appear.
ANODES AND FOCUSING COIL	The anodes accelerate and focus the electron beam so that a sharp spot is seen on the screen where the beam impacts. The acceleration occurs because the 1st and 3rd anodes are positive and focusing is achieved by varying the voltage applied to the 2nd anode which is negative relative to the other anodes.
X and Y PLATES	By varying the voltage across the X and Y plates, the beam of electrons can be made to move left or right and up or down across the screen. In a basic weather radar, the beam of electrons is made to move in the same direction as the radar pulses emitted by the aerial. The time taken by the beam of

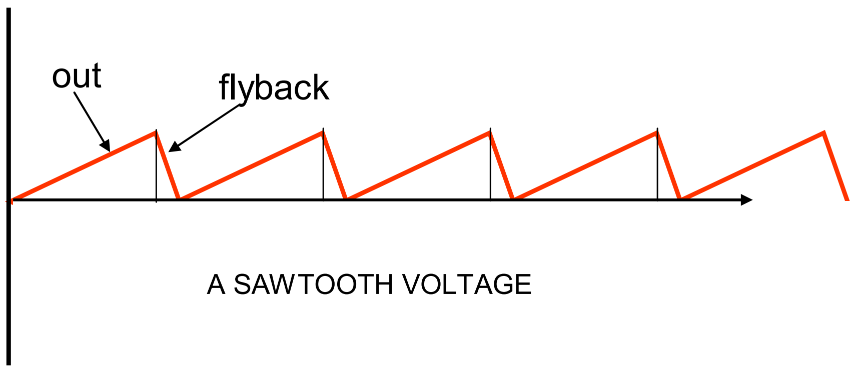
electrons to move from the origin to the edge of the screen is the same as the time taken by the pulses to travel out and back to the limits of range.

Some additional notes on the CRT illustrated above:

- The diagram shows an electrostatic deflection tube.
- The cathode is earthed and the tube is evacuated.
- It has a graphite internal coating to provide a return path for the electrons and it may have an external mu-metal shield to prevent unwanted radiation.



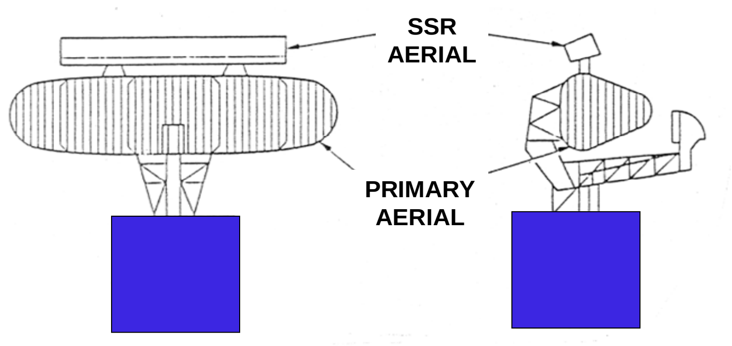
When the electron beam reaches the edge of the screen, the voltage difference across the X and Y plates reverses so that the beam rapidly returns to the origin. This process of "slow-out/fast-back" is achieved by what is known as a sawtooth voltage.



GROUND RADAR

Ground radar is widely used by ATC to provide information about the precise position and velocity of aircraft. Using secondary radar principles, equipment can also supply other useful data such as identification and height. Radar contributes to the safety and expeditious movement of air traffic along airways which are corridors of controlled airspace. Near airports radar may be used to sequence aircraft onto final approach, as a final approach aid and to help in separation after take-off.

Long range Surveillance Radar is used to provide surveillance along airways. Secondary radar may be used in conjunction with primary with the SSR (secondary surveillance radar) antenna mounted on top of the primary radar antenna.



TMA (Terminal Area) Surveillance Radar provides surveillance of aircraft close to major airports.

Aerodrome Surveillance Radar (ASR) is used to identify aircraft and to vector them on to final approach.

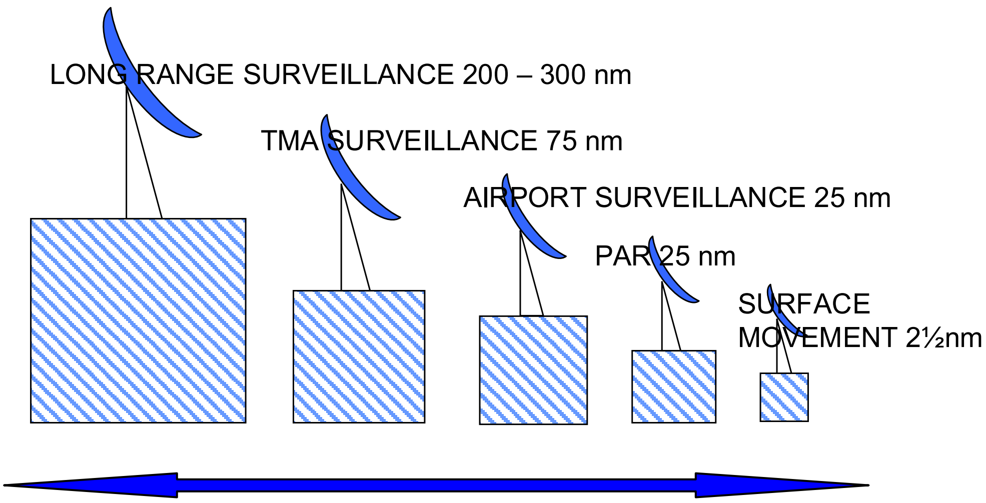
Precision Approach Radar (PAR) can be used to detect and display the azimuth, range and elevation of an aircraft on final approach. It is used by air traffic controllers to provide the pilot with a precision approach or to monitor non-radar approaches.

Surface Movement Radar provides ATC with the means of controlling aircraft and vehicles moving on aprons, taxiways and runways. In the UK Surface Movement Radar operates in the SHF band. EHF was found to be unsatisfactory because precipitation could block out returns.

FACTORS INFLUENCING RADAR CHARACTERISTICS

Range and Power: Long range requires high transmitter power.
Power and Wavelength: It is generally true that the shorter the wavelength, the less the power that can be generated by a transmitter.
Range and PRF: Long range requires low pulse recurrence frequency
Beam Width and Antenna Dimensions: An ATC radar system may require a narrow beam for accurate tracking of aircraft or a broad beam for search purposes. Larger antennas are capable of producing narrower, more focused beams.
Beam Width and Wavelength: For a given antenna dimension, the longer the wavelength the wider will be the beam.
Range and Pulse Length: The ability to display targets at short range requires short pulse lengths.
Weather Penetration and Wavelength: It is generally true that the longer the wavelength, the greater the likelihood of penetrating weather.

CHARACTERISTICS OF PRIMARY GROUND RADARS



LONG (50 cm)	Wavelength	SHORT (1 cm)
LOW (600 MHz)	Frequency	HIGH (34 GHz)
UHF	Frequency Band	EHF or SHF
NO	Weather Clutter	YES
LONG	Pulse Length	SHORT
LARGE	Aerial Size	SMALL
WIDE	Beam Width	NARROW
LOW	PRF	HIGH

MOVING TARGET INDICATOR (MTI)

A MTI system displays echoes from moving targets such as aircraft and rejects those from fixed objects such as buildings and hills. This is achieved by detecting the **Doppler shift** in the frequency of the echoes from moving aircraft. For fixed objects, the frequency of the radar wave will be the same before and after reflection and such echoes are cancelled in the receiver.

REJECTION OF RAIN CLUTTER

Reflections and scattering of the radio energy by raindrops can cause masking of echoes from aircraft which the ground radar is attempting to track. This problem can be reduced by **circular polarisation** which allows the receiving antenna to reject returning energy from spherical raindrops but to accept returns from the irregular shapes of aircraft.

RADAR APPROACH

A radar approach is an instrument approach procedure that utilises Aerodrome Surveillance Radar (ASR) or Precision Approach Radar (PAR). During a surveillance radar approach (SRA) the controller has an indication on the display of the aircraft's range and bearing. The controller is able to give the pilot fly left or fly right instructions so that the aircraft will maintain the centreline. As the surveillance radar gives no height information, the controller can only assist the pilot in the vertical plane by providing range from touchdown and a check height based on the appropriate glidepath, typically 3°.

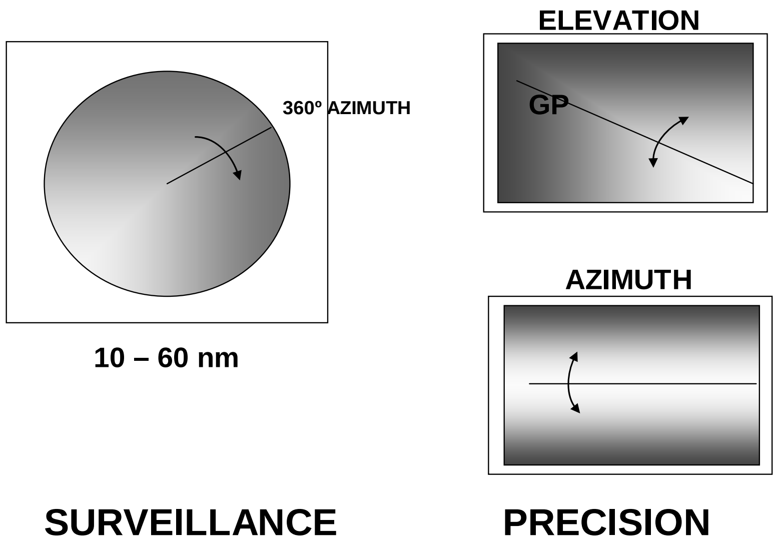
The following is an example of the SRA controller's instructions:

"You are right of the centre line, turn left two degrees, heading 236 degrees.

At four miles to touchdown, should be passing 1270 feet. Four miles now."

Surveillance radar approaches are normally terminated at 2 nm from touchdown but when a high resolution radar is in use the radar approach may be continued to ½ nm.

Precision Approach Radar (PAR) is able to provide a more accurate and more complete talk-down as the controller can monitor the height of the aircraft. PAR utilises two independent radars consisting of an azimuth element that scans 10° either side of the extended centre line and an elevation element that scans through 7° in the vertical plane, from 1° below to 6° above the glide path. The radar returns are displayed on two separate screens on which the centreline, glidepath and range markers are superimposed electronically. During a PAR talkdown the pilot is given instructions to fly left or right to maintain the centreline and information on whether the aircraft is above or below the glidepath with a corresponding instruction regarding the required rate of descent.



PAR and SRA approaches are generally used by military aircraft and civil aircraft are only authorised to use such facilities in an emergency where no pilot-interpreted instrument approach aid such as ILS or MLS is available. Where PAR is installed, ILS approaches will be monitored by PAR whenever the weather is below prescribed minima or when requested by the pilot.

As PAR approaches are height monitored and more accurate, the obstacle clearance height (OCH) and decision height (DH) will be lower for a PAR than for a SRA approach.

SUMMARY OF RADAR FORMULAE

Below is a summary of formula that can be used in the following worksheets.

DIST= SPEEDxTIME

SPEED: C= 300×10^6m/s. However as radar systems often measure time in microseconds (millionths of a second) a more appropriate figure of 300m/μsec can be used.

DIST: in metres

There is an exception to the above i.e. one formula that is separate from D=ST and that is a formula to calculate the number of cycles for a given pulse width, this was mentioned in chapter one:

No of Cycles = Freq x Pulse Width

The following formula use variations of (D=SxT)

Length of Pulse

Length of pulse = C x Pulse width

PRI:

TIME = 2xRange/SPEED
or
PRI = 1/PRF

PRI can also be calculated by using the 'radar mile' figure of 12.359 μsec

PRI = 12.359 x Range (nm)

PRF:

PRF= 1/PRI

If PRF = 1/PRI then:
PRI = 1/PRF

Max Range:

Max Range = C x 1/PRF x ½
or
Max Range = C/(2x PRF)

Alternative PRF formula:

PRF = C/(2xMax Range)

WORKSHEET - RADAR PRINCIPLES AND GROUND RADAR

1. A radar with a high PRF has a:-

   (a) narrow beam width
   (b) short pulse length
   (c) large pulse width
   (d) short pulse recurrence interval

2. The maximum range of a primary radar depends upon many factors including transmitter power. Assuming that power is the limiting factor, to double the range transmitter power must be:

   (a) increased by 100%
   (b) doubled
   (c) four times
   (d) sixteen times

3. Radar attenuation increases with:

   (a) increase in frequency
   (b) decrease in frequency
   (c) increase in pulse length
   (d) decrease in pulse length

4. The minimum range of a radar is a function of:

   (a) PRF
   (b) pulse width
   (c) beam width
   (d) Pulse recurrence interval

5. When compared with primary radar, secondary radar:

   (i) requires more transmitter power to achieve the same range
   (ii) can be coded to carry data
   (iii) can use smaller aerials

   (a) All the statements are true
   (b) Only (ii) and (iii) are true
   (c) Only (ii) is true
   (d) Only (iii) is true

6. In a CRT, control of brilliance is achieved by varying the voltage to the _______ and control of focus by varying the voltage to the ________.

(a) cathode / 2nd anode
(b) anode / cathode
(c) grid / 2nd anode
(d) heater / grid

7. Beam width affects resolution in _______ and close targets may not be separated ___________.

(a)	range	at short range
(b)	azimuth	at long range
(c)	range	at long range
(d)	azimuth	at short range

8. Accurate narrow radar beams are best produced by transmitter energy with _______ wavelengths using __________ antennas.

	WAVELENGTH	ANTENNA
(a)	long	large
(b)	short	large
(c)	short	small
(d)	long	small

9. Compared with pulse radar, continuous wave radar:

(i) is more complex
(ii) is little affected by ground clutter
(iii) has no minimum range limitations

(a) All statements are true.
(b) Only statements (i) and (ii) are true
(c) Only statements (i) is true
(d) Only statements (ii) and (iii) are true.

10. What is the maximum PRF that can be used by a radar that is designed to detect targets at a range of 335 km?

(a) 242
(b) 447
(c) 484
(d) 895

11. The principal factor that determines the ability of a ground radar system to penetrate weather is:

(a) wavelength
(b) pulse length
(c) PRF
(d) beam width

12. The maximum range of a Surface Movement Radar is approximately:

(a) 1 nm
(b) $2^1/_2$ nm
(c) 5 nm
(d) 10 nm

13. Long range radars tend to have ______ wavelengths and ______ pulse lengths.

(a)	long	short
(b)	short	long
(c)	long	long
(d)	short	short

14. Which of the following statements are true with reference to PAR (precision approach radar)?

(i) It is used to detect and display the azimuth, range and elevation of aircraft on final approach.
(ii) It can be used to provide a 'talk down' precision approach service in place of ILS
(iii) It can be used to monitor aircraft making an ILS approach.

(a) All statements are true
(b) Only (ii) and (iii) are true
(c) Only (i) and (ii) are true
(d) Only (i) and (iii) are true

15. (Students for UK exams only-see AIP RAC 2-2) ATC will normally assume that an aircraft carrying out a surveilance radar approach is using a ______ pressure datum.

(a) QNH (Local)
(b) QNH (Area)
(c) QNE
(d) QFE

16. The type of radar used to identify aircraft and to vector them on to final approach is :

(a) Long range surveillance radar
(b) Aerodrome surveillance radar
(c) TMA surveillance radar
(d) Precision Approach radar.

17. Long Range Surveillance radars operate in the ________ frequency band whereas Surface Movement radars operate in the _____ frequency band.

(a)	SHF	EHF
(b)	UHF	SHF
(c)	EHF	SHF
(d)	VHF	EHF

18. What method is used by ground radar to eliminate returns from fixed objects such as buildings and hills?

(a) reduced receiver gain
(b) pulse technique
(c) Doppler effect
(d) circular polarisation

19. What method is used by ground radar to reduce rain clutter?

(a) reduced receiver gain
(b) pulse technique
(c) Doppler effect
(d) circular polarisation

20. During a surveillance radar approach the pilot is provided with:

(a) advise on whether the aircraft is above or below the glidepath
(b) the height of the aircraft at each nautical mile to touchdown
(c) range and check heights at appropriate intervals
(d) headings to steer but no advise to assist the aircraft to maintain the glide path

21. A high resolution surveillance radar approach may be continued to:

(a) 2 nm from touchdown.
(b) 1 nm from touchdown.
(c) ½ nm from touchdown.
(d) touchdown.

22. Which of the following statements is true with reference to PAR?

(a) It utilises a single radar which scans in both azimuth and elevation planes.
(b) The controller informs the pilot of the height of the aircraft at regular intervals.
(c) As PAR is more accurate than SRA, it permits the use of a lower decision height.

(d) PAR can be used to monitor an ILS approach

WORKSHEET – RADAR RANGING

1. If the slant range is 30 km, what is the time interval between the transmission of a pulse and the reception of it's echo?

2. An echo from a target is received 75 μsec after the pulse has been transmitted. What is the range of the target in nm?

3. How many microseconds are there between the time of transmission and the time of reception of the echo if the range is 54 nm?

4. A radar pulse is transmitted on a carrier frequency of 10000 MHz. If the pulse length is 3.5 μsec, how many cycles of the carrier frequency occur during the transmission of one pulse?

5. What is the minimum range in nm for a radar transmitter when the pulse length is 30 μsec?

6. What is the maximum range in km of a radar whose PRF is 500?

ADDITIONAL RADAR RANGING QUESTIONS

7. A radar has a PRF of 750 pps. Calculate the MTR:-

   (a) 108 nm
   (b) 121 nm
   (c) 216 nm

8. An echo on a CRT registers a time interval of 280 μsec out and return. Ignoring fly back determine the range of the target.

   (a) 45.36 nm
   (b) 22.68 nm
   (c) 26.04 nm

9. A radar is designed to have a maximum range of 350 nm. Determine the required PRF.

(a) 462.86 pps
(b) 432.09 pps
(c) 231.43 pps

10. A radar is designed to have a minimum range of 1200 m. Determine the required pulse width.

(a) 12 μsec
(b) 8 μsec
(c) 6 μsec

11. The PRF of a radar installation is 570 pps. What is the time interval between successive transmissions of the leading edges of the pulses?

(a) 1754.39 μsec
(b) 1140.00 μsec
(c) 1643.85 μsec

12. A particular radar installation is designed to operate to a maximum range of 180 nm. If three-tenths of the cycle is used for flyback, what is the PRF required?

(a) 3175 pps
(b) 2222 pps
(c) 315 pps

13. A radar tracking system is designed to give radar coverage along an approach path to a runway that measures 50 km from the radar installation to the beginning of the approach. Calculate the timing of the transmission pulses to meet the maximum range requirements.

(a) 3240 pps
(b) 3000 pps
(c) 2870 pps

14. If the above radar system operated on a carrier frequency of 13.6 GHz and a pulse width of 22 μsec, how many transmission cycles represent one pulse?

(a) 161 765 cycles
(b) 618 182 cycles
(c) 299 200 cycles