

Microwave Engineering & Radar System (315342)

Model Question Paper — Set C · Model Answers

Q.1

a) Dominant mode.

2 M

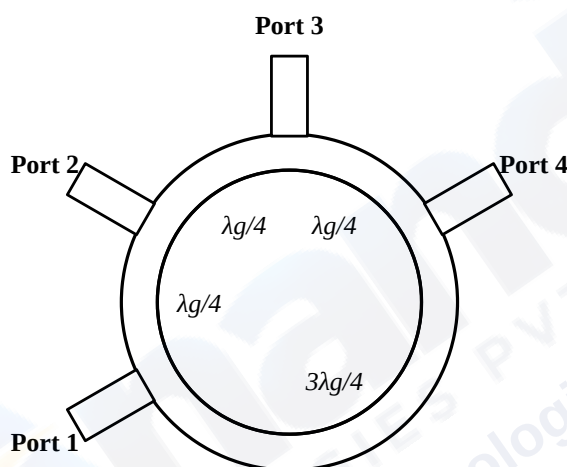
Dominant mode: the mode having the **lowest cut-off frequency** (longest cut-off wavelength) in a waveguide. It is the first mode to propagate, so a guide operated between the first and second cut-off carries only this mode.

Rectangular waveguide: TE_{10} ($f_c = c/2a$, $\lambda_c = 2a$). Circular waveguide: TE_{11} ($\lambda_c = 3.41 r$).

(Definition 1 M, two modes 1 M)

b) Rat-race junction.

2 M



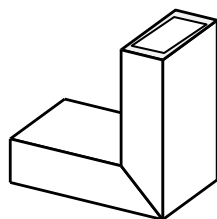
Rat-race junction (hybrid ring), mean circumference $1.5 \lambda_g$

Four ports on a ring of mean circumference $1.5 \lambda_g$; spacing $\lambda_g/4$ between ports 1-2, 2-3, 3-4 and $3\lambda_g/4$ between ports 4-1. Power at port 1 divides equally to ports 2 and 4; port 3 gets nothing.

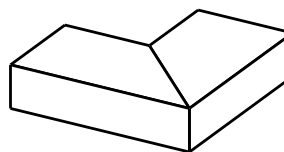
(Sketch with labels 2 M)

c) E-plane and H-plane corners.

2 M



E-plane corner (mitred, turns in plane of b)



H-plane corner (mitred, turns in plane of a)

A corner is a sharp (mitred) 90° bend; the 45° mitre reduces reflections.

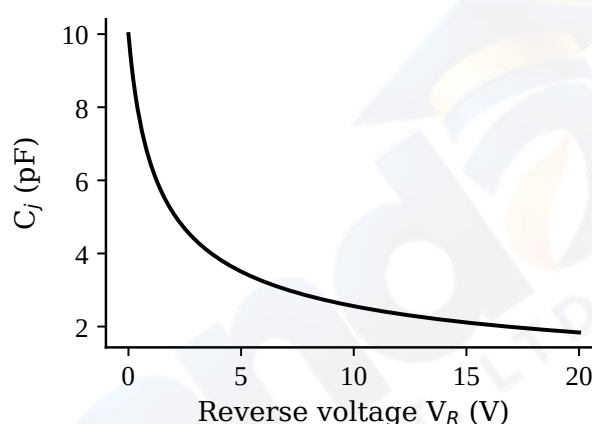
(Each sketch 1 M)

d) Varactor diode symbol and applications.

2 M



Symbol of varactor diode



Varactor: junction capacitance falls as reverse voltage rises ($C \propto 1/\sqrt{(V_0 + V_R)}$)

1. Electronic tuning of oscillators (VCO) and filters.
2. Parametric amplifiers and frequency multipliers (harmonic generators).
3. Frequency modulators and phase shifters; automatic frequency control (AFC).

(Symbol 1 M, two applications 1 M)

e) PRF and maximum unambiguous range.

2 M

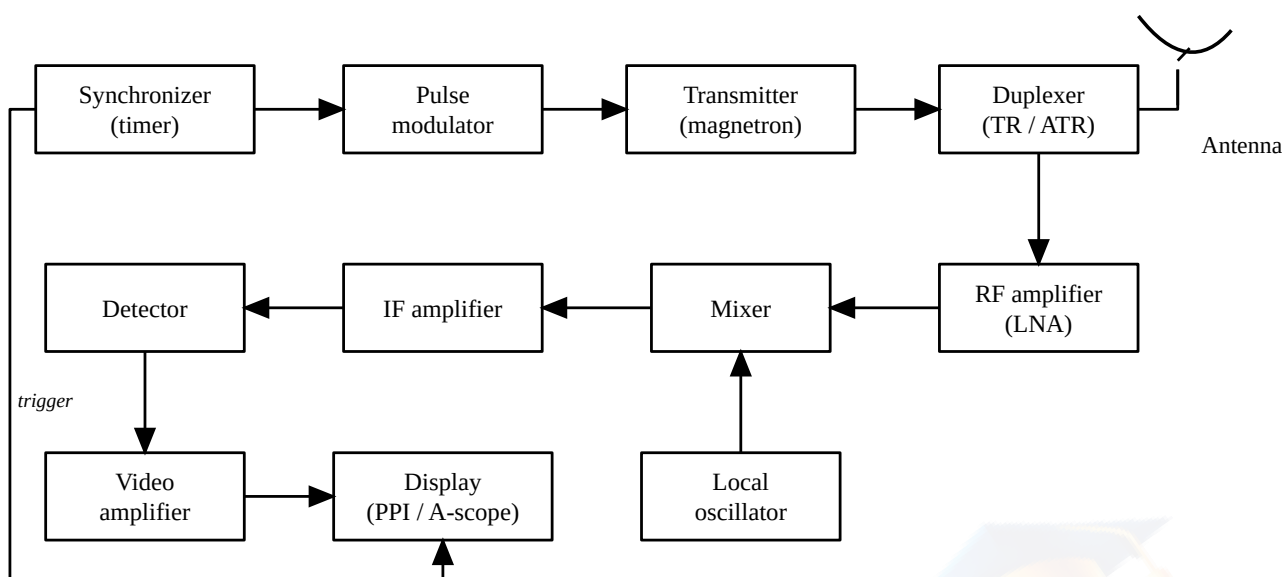
PRF (pulse repetition frequency): the number of pulses transmitted by a pulse RADAR per second. $PRF = 1/PRT$, where PRT is the time between the start of successive pulses.

$$R_{un} = c/(2 PRF) = 3 \times 10^8 / (2 \times 2000) = 75000 \text{ m} = \mathbf{75 \text{ km}}$$

(Definition 1 M, calculation 1 M)

f) Block diagram of basic pulse RADAR.

2 M



Block diagram of basic pulse RADAR

(Correct block diagram 2 M)

g) RADAR clutter and its types.

2 M

Clutter: unwanted RADAR echoes from objects other than the targets of interest, which mask or confuse the wanted target echoes on the display.

Types: (1) **Surface clutter** — *land clutter* (ground, buildings, hills, trees) and *sea clutter* (sea waves); (2) **Volume clutter** — rain, clouds, snow, chaff; (3) **Point clutter** — birds, insects, isolated towers (angels).

(Definition 1 M, types 1 M)

Q.2

a) IEEE / OSHA standards and band designations.

4 M

Role of standards:

- **IEEE** (Institute of Electrical and Electronics Engineers) defines the standard letter designations of RADAR/microwave frequency bands (IEEE Std 521) so that equipment, literature and frequency allocation use common names; IEEE C95.1 gives safety levels for human exposure to RF / microwave fields.
- **OSHA** (Occupational Safety and Health Administration, USA) sets legal limits for workers' exposure to non-ionising radiation — 10 mW/cm² power density averaged over 6 minutes for 10 MHz – 100 GHz — and requires warning signs, protective measures and training.
- Together they ensure compatibility of equipment, efficient use of spectrum and safety of personnel.

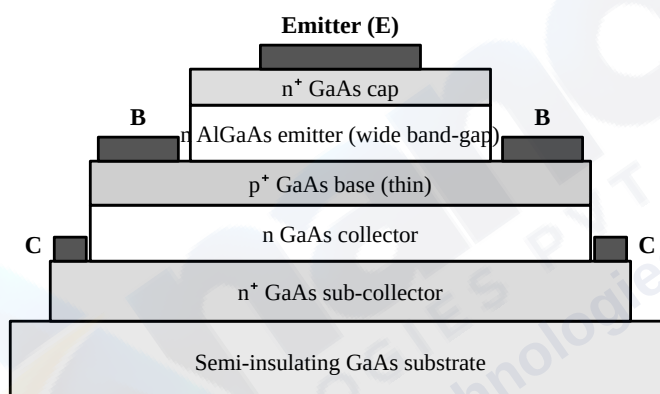
IEEE band designations:

Band	Frequency (GHz)	Typical use
L	1 – 2	GPS, mobile, long-range surveillance radar
S	2 – 4	Weather/ATC radar, Wi-Fi 2.4 GHz, microwave oven
C	4 – 8	Satellite TV/communication, Wi-Fi 5 GHz
X	8 – 12	Marine & police radar, missile guidance
Ku	12 – 18	Satellite (DTH) broadcasting
K	18 – 27	Radar, astronomy
Ka	27 – 40	Satellite, high-resolution radar, 5G
V	40 – 75	mm-wave links
W	75 – 110	Automotive radar (77 GHz)
mm	110 – 300	Research, imaging

(Role of IEEE 1 M, OSHA 1 M, bands 2 M)

b) HBT.

4 M



Heterojunction bipolar transistor (HBT) — AlGaAs/GaAs structure

Principle: An HBT is a bipolar transistor in which the emitter is made of a **wider band-gap** material (n-AlGaAs) than the base (p⁺-GaAs). The extra valence-band barrier at the heterojunction blocks holes from being injected from base into emitter, while electrons flow easily from emitter to base. Hence the emitter injection efficiency stays high even when the base is very heavily doped.

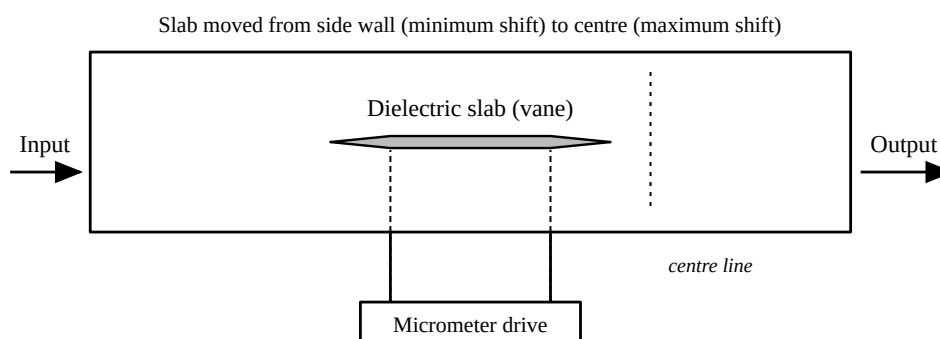
- Heavily doped, very thin base → low base resistance and short base transit time → very high f_T and f_{max} (hundreds of GHz).
- Lightly doped emitter → low emitter–base capacitance.
- High current gain, high power density, good linearity.

Applications: power amplifiers in mobile phones and Wi-Fi, microwave oscillators (low phase noise), high-speed digital and optical-fibre circuits, satellite and RADAR transmitters.

(Diagram 1 M, principle 2 M, applications 1 M)

c) Dielectric-vane phase shifter.

4 M



Dielectric-vane phase shifter (top view of rectangular waveguide)

Construction: A thin slab (vane) of low-loss dielectric (e.g. polystyrene / Teflon) is placed inside a rectangular waveguide parallel to the E field (narrow walls). Its ends are tapered to avoid reflections. The slab is supported by thin rods and can be moved across the broad dimension by a micrometer drive.

Working: The dielectric slab increases the effective permittivity seen by the wave, so the phase constant β increases (guide wavelength decreases) and the wave gets an extra phase delay. In TE_{10} mode the E field is zero at the side walls and maximum at the centre: with the slab at the side wall the phase shift is minimum; as it is moved towards the centre the phase shift increases to maximum. Phase shift $\phi = (\beta_e - \beta_0) \times l$, where l = length of slab. The micrometer is calibrated directly in degrees.

Uses: phased-array antennas, bridge measurements, balancing of microwave circuits.

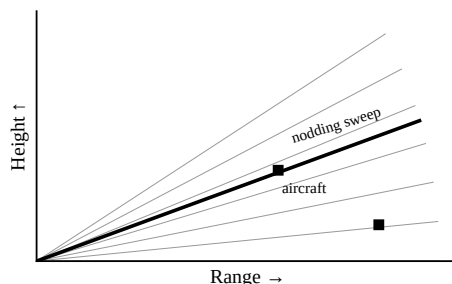
(Diagram 2 M, working 2 M)

d) A-scope vs PPI vs RHI.

4 M



A-scope display (range vs echo amplitude) PPI (Plan Position Indicator): range and azimuth (map-like view)



RHI (Range Height Indicator): range vs elevation / height

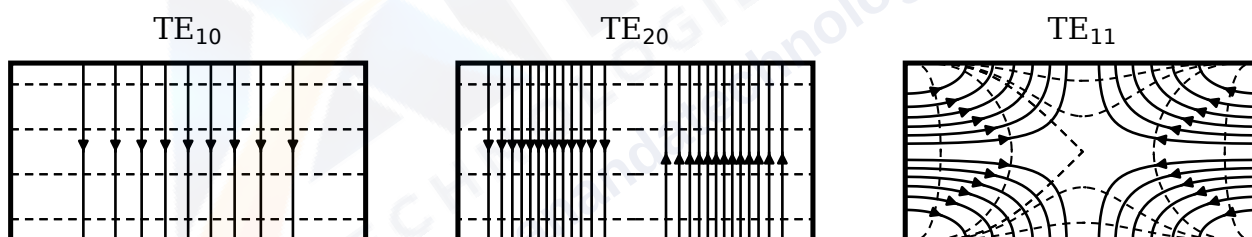
Parameter	A-scope	PPI	RHI
Information shown	Range and echo amplitude	Range and azimuth (bearing)	Range and elevation / height
Type of display	Deflection modulated (vertical pips)	Intensity modulated, polar (map)	Intensity modulated, sector
Time base	Linear horizontal sweep	Radial sweep rotating with antenna	Radial sweep nodding with antenna
Antenna scan	Fixed direction / tracking	360° azimuth rotation	Vertical (nodding) scan
Use	Tracking, ranging, testing	Surveillance, ATC, navigation, weather	Height-finding RADAR, precision approach

(Sketches 1 M, four points 3 M)

Q.3

a) Field patterns TE_{10} , TE_{20} , TE_{11} .

4 M



Field patterns in rectangular waveguide (cross-section): solid = E lines, dashed = H lines

- TE_{10} : one half-wave variation of E along a (maximum at centre), none along b.
- TE_{20} : two half-wave variations along a — E is in opposite directions in the two halves, zero at the centre.
- TE_{11} : one half-wave variation along both a and b; E lines curve from one wall to the adjacent wall (E_x and E_y both present).

(TE_{10} 1 M, TE_{20} 1½ M, TE_{11} 1½ M)

b) Range equation and factors affecting range.

4 M

$$R_{\max} = [P_t G A_e \sigma / ((4\pi)^2 S_{\min})]^{1/4}$$

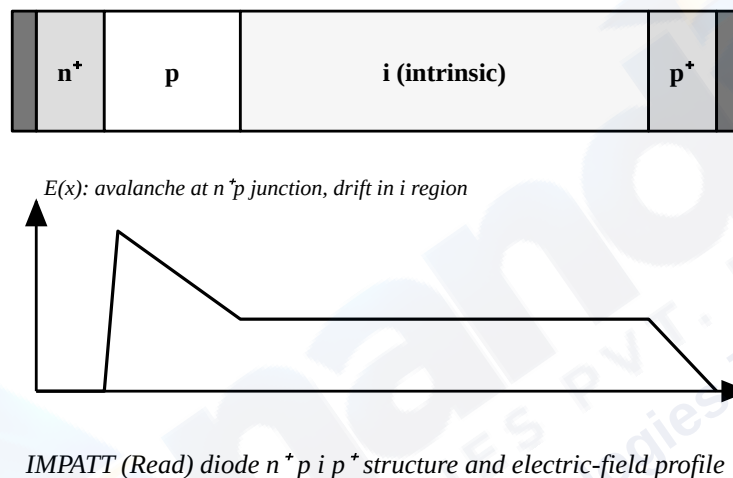
Factors affecting range:

1. **Transmitted peak power P_t :** $R \propto P_t^{1/4}$; doubling the range needs 16 times the power.
2. **Antenna gain / effective aperture:** larger antenna (higher G and A_e) gives longer range.
3. **Minimum detectable signal $S_{\min}$ (receiver sensitivity):** lower noise figure / bandwidth $\rightarrow$ smaller $S_{\min} \rightarrow$ larger range.
4. **RADAR cross-section σ** of the target (size, shape, material, aspect).
5. **Frequency / wavelength** (for fixed aperture $G = 4\pi A_e / \lambda^2$), atmospheric attenuation and rain at high frequencies.
6. **PRF and pulse width** (unambiguous range $c/2\text{PRF}$, energy per pulse), clutter, curvature of the earth (line of sight) and antenna height.

(Equation 1 M, factors 3 M)

c) IMPATT diode.

4 M



Structure: The Read diode is an $n^+p i p^+$ structure. The n^+p junction is reverse biased near breakdown, forming a thin **avalanche region**; the intrinsic (i) layer forms the **drift region**.

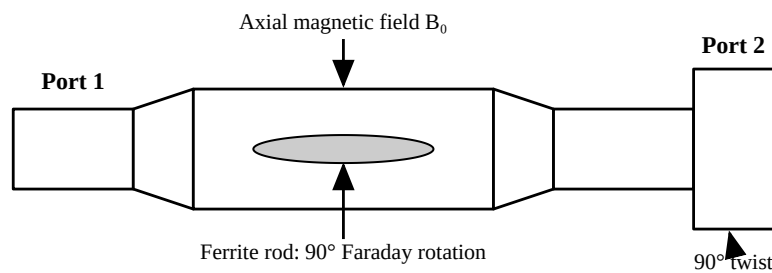
Working: An RF voltage is superimposed on the dc bias. During the positive half-cycle the field exceeds breakdown and carriers multiply by **impact ionisation**; the avalanche current builds up and reaches its peak at the end of the positive half-cycle — a **90° delay**. The generated holes then drift through the i region at saturation velocity; the **transit-time** is chosen to give another 90° delay. The total 180° phase difference between RF voltage and current means the diode shows **negative resistance** and can sustain oscillations at $f = v_d/(2L)$.

Applications: microwave oscillators and amplifiers (up to 100+ GHz), RADAR transmitters, intrusion alarms, police RADAR, mm-wave communication.

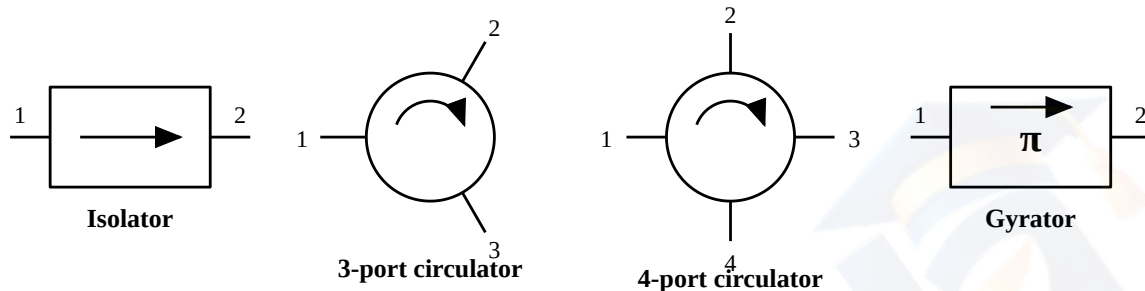
(Structure 1 M, working 2 M, applications 1 M)

d) Gyrator.

4 M



Gyrator: 90° twist + 90° Faraday rotation (180° phase shift one way)



Symbols: isolator, circulators and gyrator

Definition: A gyrator is a two-port **non-reciprocal** device which gives a **relative phase difference of 180°** for transmission from port 1 to port 2 compared with port 2 to port 1 (0° one way, π the other way).

Construction & working: A rectangular guide (TE_{10}) at port 1 changes to a circular guide containing a thin ferrite rod magnetised axially, which rotates the plane of polarisation by 90° (Faraday rotation). The output rectangular guide has a 90° twist. **Port 1 $\rightarrow$ 2:** twist and ferrite rotations add ($90^\circ + 90^\circ = 180^\circ$), so the wave emerges with 180° phase reversal. **Port 2 $\rightarrow$ 1:** the twist rotates by -90° (reciprocal) but the ferrite still rotates by $+90^\circ$ (non-reciprocal), giving net 0° . Hence a differential phase shift of 180° .

Applications: building block of isolators and circulators (with hybrid tees), non-reciprocal phase shifters, microwave switching networks.

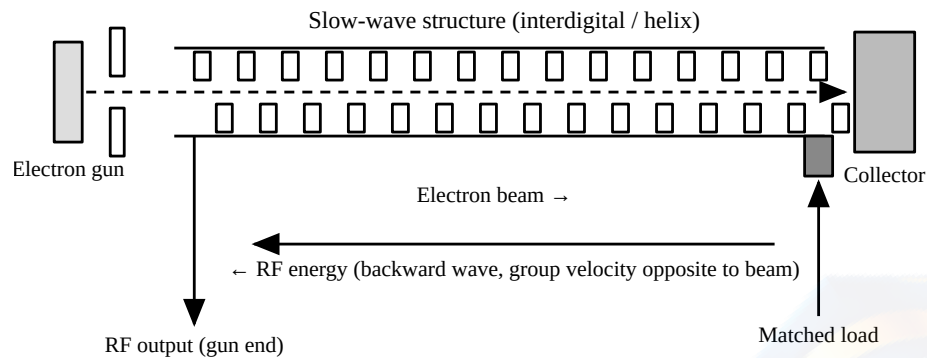
(Sketch & symbol 1 M, working 2 M, applications 1 M)

Q.4

a) Backward wave oscillator.

4 M

Frequency is tuned electronically by changing the beam voltage V_0



O-type backward wave oscillator (BWO / carcinotron) — schematic

Construction: An O-type tube similar to TWT: electron gun, a slow-wave structure (interdigital line or helix), collector and focusing magnet. The output is taken from the **gun end** of the slow-wave structure and the collector end is terminated in a matched load. There is no RF input.

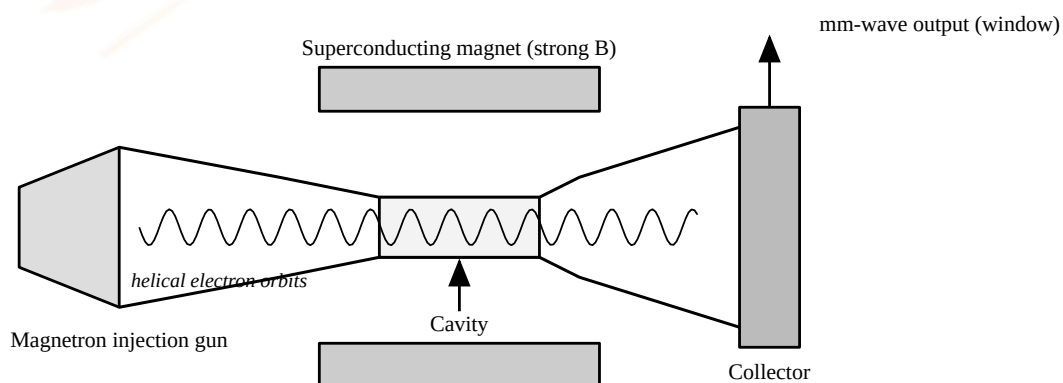
Working: The periodic slow-wave structure supports space harmonics, one of which has phase velocity in the direction of the beam while its **group velocity (energy flow) is backward**, towards the gun. Noise in the beam starts the interaction; the beam velocity-modulates and bunches, and the bunches give energy to this backward wave. Energy flows back to the gun end where it modulates the fresh beam further — an internal feedback loop, so the tube **oscillates** without an external circuit.

Features & uses: frequency is tuned **electronically over a wide range** by changing the beam voltage V_0 (carcinotron); used as swept-frequency signal sources, in test equipment, and as jammers in electronic warfare.

(Diagram 2 M, working 2 M)

b) Gyrotron.

4 M



Gyrotron (cyclotron resonance maser) — schematic

Construction: A magnetron injection gun produces an annular (hollow) electron beam. The beam enters a cylindrical open cavity placed in a very strong axial magnetic field (several tesla) from a superconducting magnet. The spent beam goes to a collector; output leaves through a window (output can be axial).

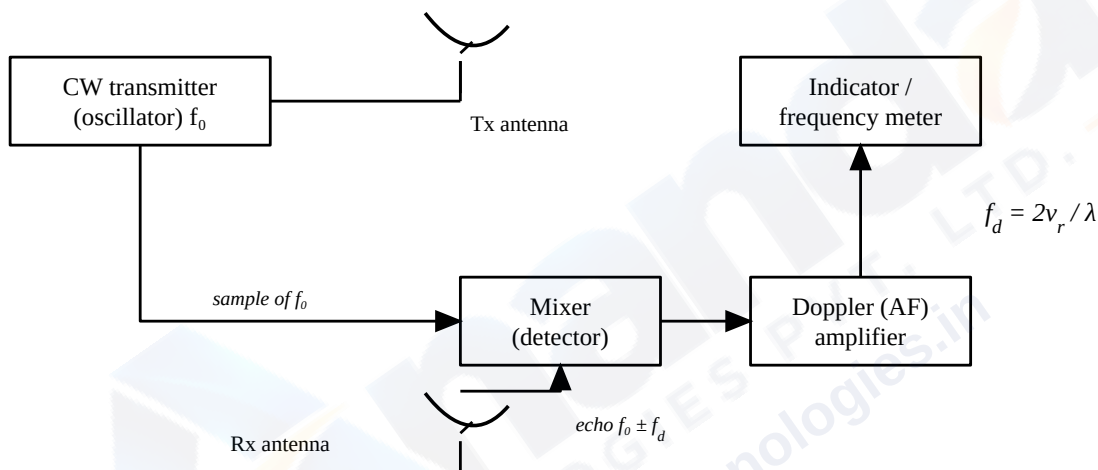
Working: In the strong magnetic field the electrons move in small **helical orbits** at the cyclotron frequency $f_c = eB/(2\pi m)$. In the cavity they interact with a TE mode whose frequency is close to f_c (or its harmonic). Because of the relativistic mass change, electrons bunch in phase of rotation (azimuthal bunching) and transfer their rotational energy to the RF field — a **cyclotron resonance maser**. The cavity can be much larger than the wavelength, so very high power at mm-waves is possible.

Applications: plasma heating in nuclear fusion (tokamaks), mm-wave RADAR, industrial material processing (ceramic sintering), high-resolution spectroscopy.

(Diagram 1 M, construction 1 M, working 1 M, applications 1 M)

c) CW Doppler RADAR and speed measurement.

4 M



Block diagram of CW Doppler RADAR

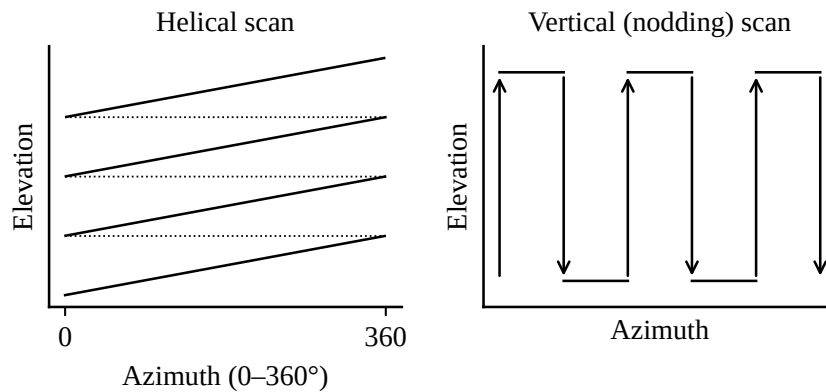
- The CW transmitter radiates a continuous wave of frequency f_0 ; a small sample of f_0 is given to the mixer as reference.
- The echo from a moving target has frequency $f_0 \pm f_d$ (+ approaching, – receding). Echoes from fixed objects have no shift.
- The mixer (detector) gives the difference frequency f_d , which lies in the audio range; it is amplified by the Doppler amplifier (which also rejects dc from fixed targets) and measured by a frequency counter / indicator.
- Speed: $v_r = f_d \lambda / 2 = f_d c / (2 f_0)$. E.g. at 10 GHz, $f_d = 2$ kHz gives $v_r = 30$ m/s = 108 km/h.

(Block diagram 2 M, explanation 2 M)

d) Scanning methods; helical and nodding scan.

4 M

Antenna scanning methods: circular (360° azimuth), sector, helical, spiral, horizontal (raster), vertical (nodding), conical (for tracking).



Radar antenna scanning patterns

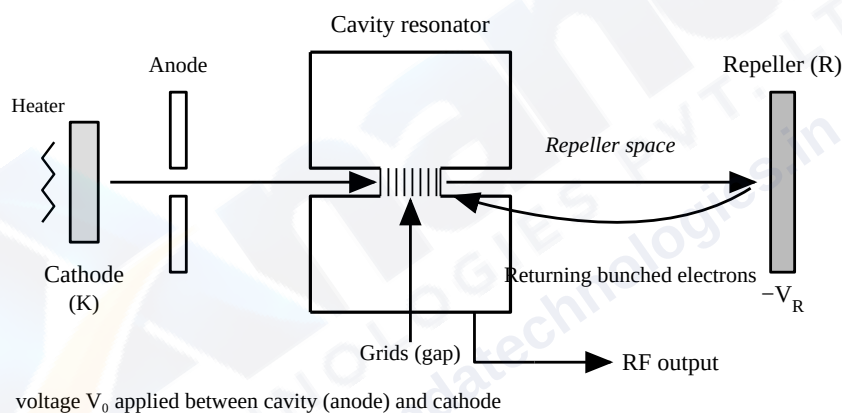
Helical scanning: the antenna rotates continuously through 360° in azimuth while its elevation is slowly increased; the beam traces a helix and searches the whole hemisphere. After reaching maximum elevation it returns to the starting elevation.

Vertical (nodding) scanning: the antenna is rapidly nodded up and down in elevation while it is slowly turned in azimuth. Used with height-finding RADAR and RHI display.

(List 1 M, each method with sketch $1\frac{1}{2}$ M)

e) Reflex klystron; $(n + \frac{3}{4})$ transit time.

4 M



Reflex klystron — schematic

Working: The beam accelerated by V_0 crosses the cavity gap and is velocity modulated by the RF gap voltage. In the repeller space the negative repeller voltage $-V_R$ turns all electrons back. Faster electrons go deeper and return later; slower ones return earlier, so they return as **bunches** through the gap. The bunches deliver energy to the cavity and maintain oscillations; output is taken by a coupling loop.

Why $(n + \frac{3}{4})$ cycles: The bunch is formed around the electron that crossed the gap when the gap voltage changed from accelerating to retarding (zero crossing). For maximum energy transfer the bunch must return when the gap field gives **maximum retardation** to the returning electrons, i.e. at the positive peak of the gap voltage. From that zero crossing to a positive peak is $\frac{3}{4}$ cycle (plus any whole number n of cycles). Hence transit time $T' = (n + \frac{3}{4})T$, $n = 0, 1, 2 \dots$ Each value of n

gives a **mode** of oscillation, selected by adjusting V_R ; frequency can also be tuned electronically over a small range by V_R .

(Diagram 1 M, working 2 M, reason 1 M)

Q.5

a) Dielectric-filled waveguide numerical.

6 M

Given: $a = 2.5 \text{ cm} = 0.025 \text{ m}$, $b = 1.25 \text{ cm} = 0.0125 \text{ m}$, $f = 5 \text{ GHz}$, $\epsilon_r = 2.25$, $\mu_r = 1$.

Velocity in the filling medium $v = c/\sqrt{\epsilon_r} = 3 \times 10^8/1.5 = 2 \times 10^8 \text{ m/s}$.

$$f_c = (v/2) \sqrt{[(m/a)^2 + (n/b)^2]}$$

i) Cut-off for TE_{10} ($m = 1$, $n = 0$): $f_{c10} = v/(2a) = 2 \times 10^8/(2 \times 0.025) = \mathbf{4.000 \text{ GHz}}$; $\lambda_c = 2a = 5 \text{ cm}$.

Cut-off for TE_{11} : $f_{c11} = (2 \times 10^8/2) \sqrt{[(1/0.025)^2 + (1/0.0125)^2]} = \mathbf{8.944 \text{ GHz}}$ → does not propagate ($f < f_c$) at 5 GHz.

ii) Free-space (medium) wavelength: $\lambda = v/f = 2 \times 10^8/(5 \times 10^9) = 4.000 \text{ cm}$.

$$\sqrt{1 - (f_c/f)^2} = \sqrt{1 - (4.000/5)^2} = 0.6000$$

iii) Guide wavelength: $\lambda_g = \lambda / \sqrt{1 - (f_c/f)^2} = 4.000/0.6000 = \mathbf{6.667 \text{ cm}}$

iv) Phase velocity: $v_p = v / \sqrt{1 - (f_c/f)^2} = \mathbf{3.333 \times 10^8 \text{ m/s}}$

v) Group velocity: $v_g = v \times \sqrt{1 - (f_c/f)^2} = \mathbf{1.200 \times 10^8 \text{ m/s}}$ (check: $v_p \cdot v_g = v^2$)

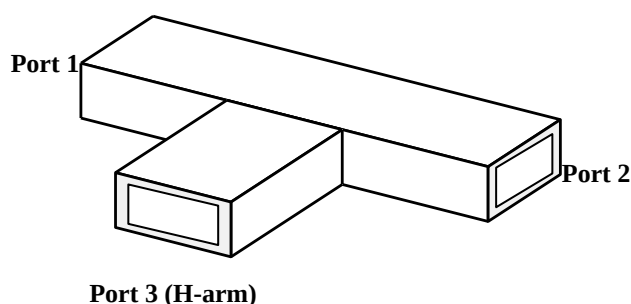
vi) Wave impedance (TE_{10}): $Z_{TE} = \eta / \sqrt{1 - (f_c/f)^2}$, $\eta = 120\pi/\sqrt{\epsilon_r} = 251.33 \Omega$ → $Z_{TE} = \mathbf{418.9 \Omega}$

Answer: $f_{c10} = 4 \text{ GHz}$, $f_{c11} = 8.944 \text{ GHz}$ (only TE_{10} propagates), $\lambda_g = 6.667 \text{ cm}$, $v_p = 3.333 \times 10^8 \text{ m/s}$, $v_g = 1.200 \times 10^8 \text{ m/s}$, $Z_{TE10} = 418.9 \Omega$.

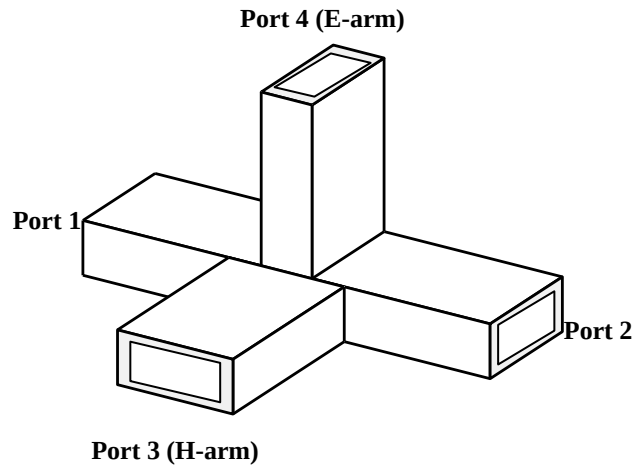
(Cut-offs 2 M, λ_g 1 M, v_p & v_g 2 M, impedance 1 M)

b) H-plane tee and magic tee; magic tee as duplexer.

6 M



H-plane tee (shunt tee)



Magic tee (hybrid tee)

H-plane tee (shunt tee): the arm is attached to the narrow wall, so its axis lies in the plane of H. Power fed at the H-arm divides equally between ports 1 and 2 **in phase**.

Properties of magic tee:

1. Input at H-arm (3) → equal, in-phase outputs at ports 1 and 2; no output at E-arm (4).
2. Input at E-arm (4) → equal outputs at ports 1 and 2, 180° out of phase; no output at H-arm.
3. E-arm and H-arm are isolated from each other.
4. Signals entering ports 1 and 2 together add at the H-arm and subtract at the E-arm.
5. When ports 3 and 4 are matched, ports 1 and 2 are also isolated (all ports matched, "magic").

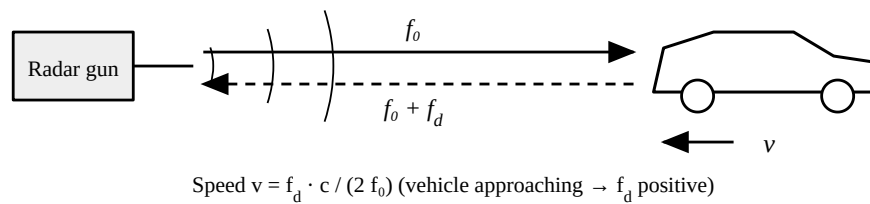
Magic tee as duplexer: Transmitter is connected to the E-arm, receiver to the H-arm, antenna to port 1 and a matched load to port 2. Transmitter power entering the E-arm divides between port 1 (antenna) and port 2 (load) and **does not reach the receiver** (E and H arms are isolated). The received echo entering port 1 divides between E-arm and H-arm, so half of it reaches the receiver. Thus one antenna is shared and the receiver is protected. (Disadvantage: 3 dB loss each way; a magic tee with gas TR tubes (balanced duplexer) avoids this.)

(Sketches 2 M, properties 2 M, duplexer 2 M)

c) RADAR applications.

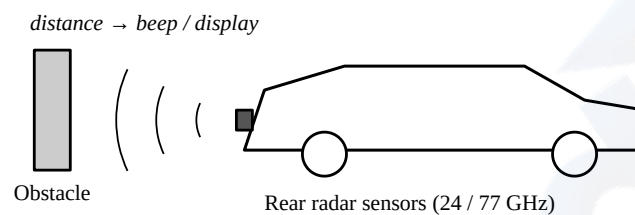
6 M

i) Vehicle speed detection: a CW Doppler RADAR gun (X / K / Ka band) is aimed at the vehicle; the Doppler shift of the echo gives the speed $v = f_d c / (2f_0)$, displayed directly in km/h.



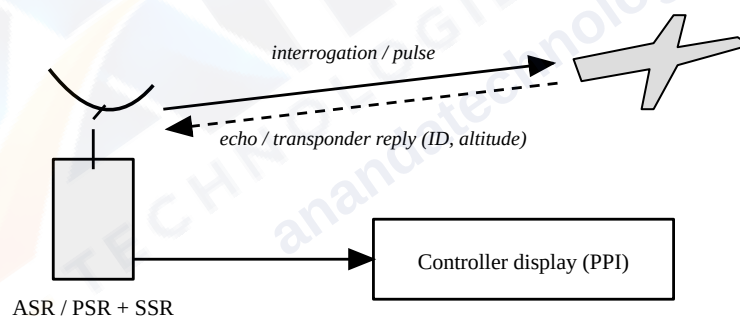
Vehicle speed detection by Doppler radar gun

ii) Vehicle parking assistance: short-range RADAR sensors (24 / 77–79 GHz) in the bumpers measure distance to obstacles behind/in front of the car; the driver gets a beep of increasing rate and a display; also used for blind-spot detection and automatic parking.



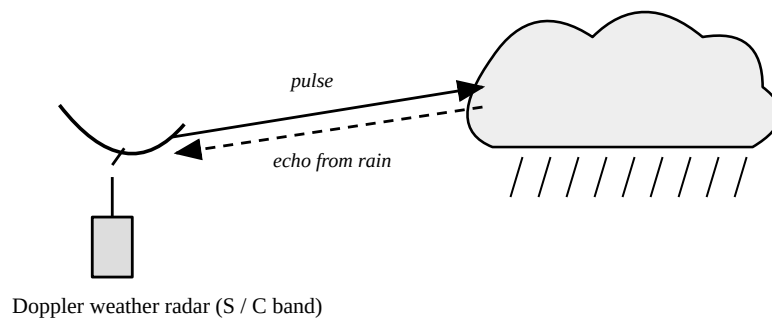
Parking assistance: short-range radar sensors in the bumper measure distance to obstacles

iii) Air traffic control: the airport surveillance RADAR (primary, PPI display) shows position of all aircraft up to about 100 km; the secondary surveillance RADAR interrogates the aircraft transponder for identity and altitude; precision approach RADAR guides landing.



Air traffic control: primary surveillance radar (PSR) + secondary radar (SSR) on the airport

iv) Weather surveillance RADAR: S / C band Doppler RADAR measures echo strength from rain, snow and hail (reflectivity) to give rainfall intensity, and the Doppler shift gives wind speed; used to track storms and cyclones and warn the public.



Weather surveillance (Doppler) radar: echoes from rain drops give rainfall intensity and wind speed

(Each application with sketch 1½ M)

Q.6

a) RADAR range and Doppler shift numerical.

6 M

i) Maximum range (same antenna: $A_e = G\lambda^2/4\pi$)

Given: $P_t = 1 \times 10^6 \text{ W}$, $G = 2000$, $f = 3 \text{ GHz}$ ($\lambda = c/f = 10 \text{ cm}$), $\sigma = 5 \text{ m}^2$, $S_{\min} = 1.00 \times 10^{-12} \text{ W}$.

$$R_{\max} = [P_t G^2 \lambda^2 \sigma / ((4\pi)^3 S_{\min})]^{1/4}$$

$$\text{Numerator} = 1 \times 10^6 \times 2000^2 \times (0.1)^2 \times 5 = 2.000 \times 10^{11}$$

$$\text{Denominator} = (4\pi)^3 \times 1.00 \times 10^{-12} = 1984.4 \times 1.00 \times 10^{-12} = 1.984 \times 10^{-9}$$

$$R_{\max} = (1.008 \times 10^{20})^{1/4} = 1.002 \times 10^5 \text{ m} \approx \mathbf{100.20 \text{ km}}$$

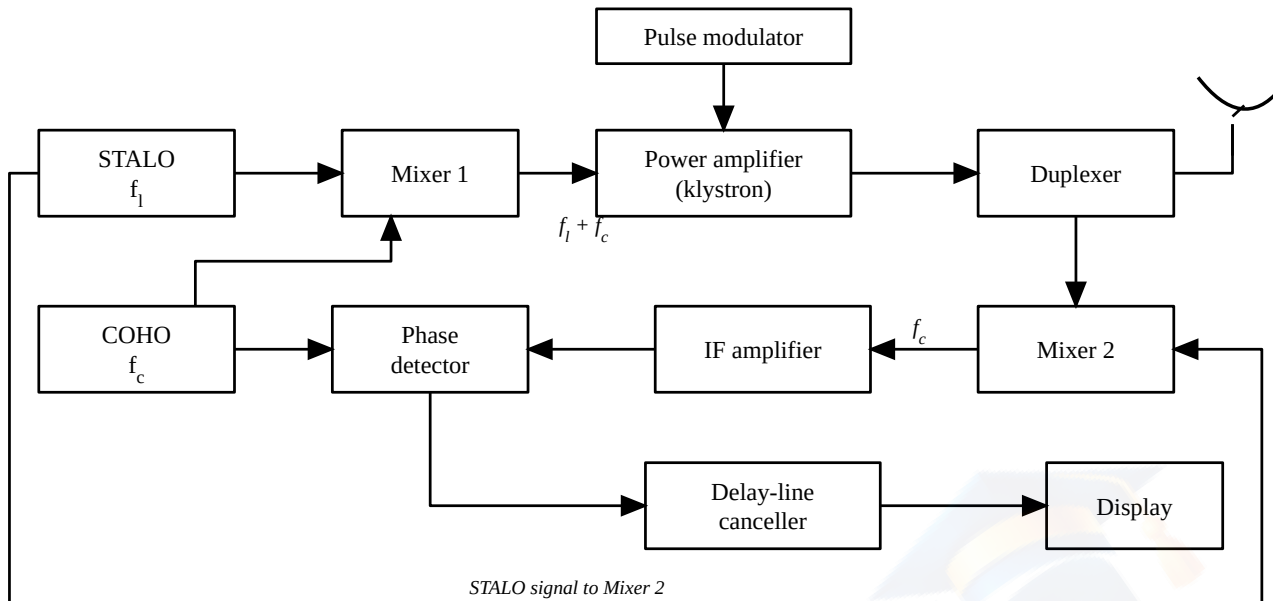
ii) Doppler shift: $v_r = 900 \text{ km/h} = 250 \text{ m/s}$; $\lambda = 0.1 \text{ m}$.

$$f_d = 2v_r/\lambda = 2 \times 250/0.1 = \mathbf{5000 \text{ Hz} = 5 \text{ kHz}}$$

(Range 4 M, Doppler 2 M)

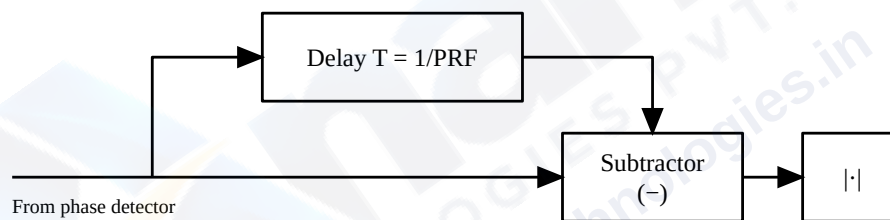
b) MTI RADAR, delay-line canceller and blind speeds.

6 M



Block diagram of MTI RADAR (coherent, power-amplifier type)

Transmitted frequency $f_l + f_c$ is obtained from STALO and COHO; the received echo is converted to IF using STALO and compared in the phase detector with the COHO. Fixed targets give the same output on every pulse; moving targets give an output that changes from pulse to pulse.



Single delay-line canceller: echo of a fixed target is cancelled

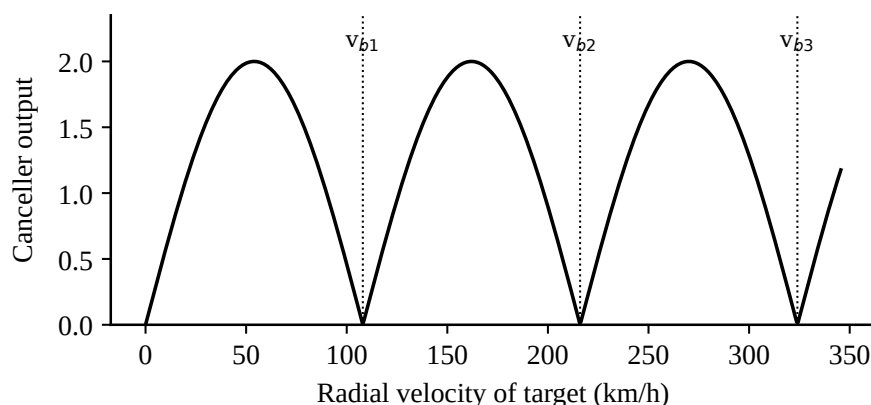
Delay-line canceller: the phase-detector output is applied to a subtractor directly and through a delay line of delay $T = 1/\text{PRF}$. The subtractor output is the difference of two successive echoes: fixed-target echoes are identical and cancel; moving-target echoes differ and are passed (then rectified and displayed). It acts as a comb filter with nulls at 0, PRF, 2PRF ...

Blind speed: the radial target speed for which the Doppler shift equals a multiple of the PRF, so the target moves exactly $n\lambda/2$ between pulses, its echo phase is the same on every pulse, and it is cancelled like a fixed target. $v_b = n \lambda f_p / 2$.

$$\lambda = c/f = 3 \times 10^8 / (6 \times 10^9) = 0.05 \text{ m.}$$

$$\text{First blind speed } v_{b1} = \lambda f_p / 2 = 0.05 \times 1200 / 2 = 30 \text{ m/s} = 108 \text{ km/h}$$

$$\text{Second blind speed } v_{b2} = 2 \times v_{b1} = 60 \text{ m/s} = 216 \text{ km/h}$$

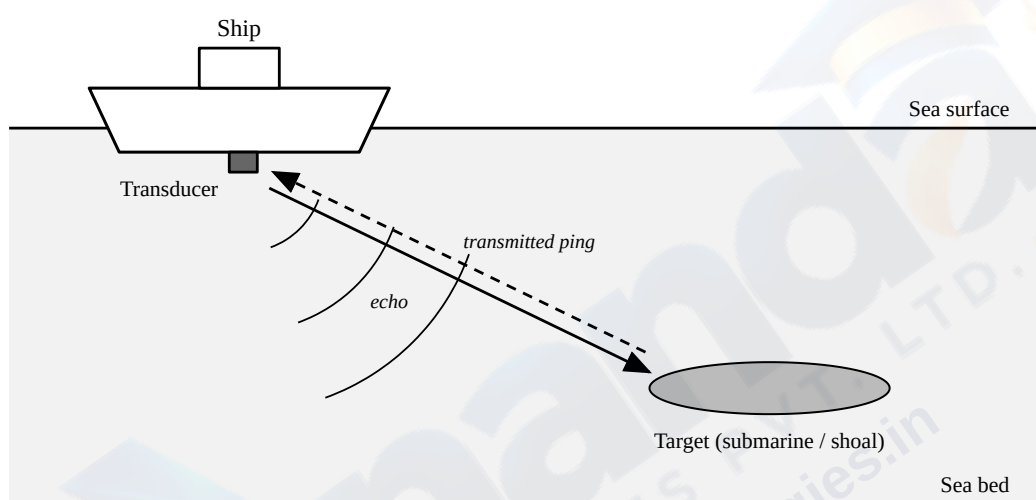


Frequency response of single delay-line canceller: zero output at blind speeds

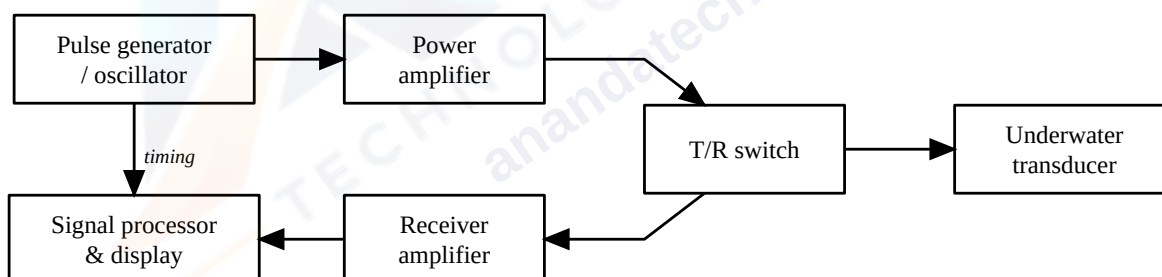
(Block diagram 2 M, canceller 1 M, blind speed definition 1 M, calculation 2 M)

c) SONAR working; SONAR vs RADAR.

6 M



SONAR: transducer sends sound pulse; echo from target measured ($R = v t / 2$)



Block diagram of active SONAR

Working principle: A pulse of ultrasonic energy is produced by the transmitter and converted to sound by the underwater transducer. The sound pulse travels through water at about 1500 m/s, is reflected by the target and returns as an echo, which the transducer converts back to an electrical signal. The receiver amplifies it and the processor measures the time t : **range $R = v t / 2$** . Bearing comes from the transducer direction, and speed from the Doppler shift.

Parameter	SONAR	RADAR
Wave used	Sound / ultrasonic (mechanical) waves	Electromagnetic (radio / microwave) waves
Medium	Water (needs a medium)	Air / space (no medium needed)
Speed of wave	≈ 1500 m/s in sea water	3×10^8 m/s
Frequency	About 1 kHz – 100 kHz	About 300 MHz – 100 GHz
Transducer / antenna	Piezoelectric / magnetostrictive transducer, hydrophone	Dish / horn / array antenna
Range	Few km to tens of km	Hundreds of km
Applications	Submarine detection, depth finding, fishing	Aircraft detection, ATC, weather, navigation

(Diagram 2 M, principle 1 M, any four points 3 M)

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