CHAPTER 13
Electronic Warfare

13.1 Radar:

Although many applications in this chapter started out in military affairs yet they have found roots in civilian applications as well. Radar is a system for ranging, detection and location of objects such as aircraft, ships etc. It has become also a means for imaging and locating targets in $3D$. This is done through processing a signal originally transmitted by the system and then reflected from the object as echo. By comparing the echo with the original signal, information about the object can be obtained. Such a system is called an active system since energy is radiated by a source (usually electronic). It can operate in darkness, fog, rain, i.e. in all weather condition with high accuracy. Ultrasonic radar imaging is also used to image a fetus and sonar radar is used in undersea detection. The basic principle of radar is illustrated (Fig. 13.1). A transmitter generates an electromagnetic signal in the form of a short pulse of a sine wave that is radiated into space by an antenna. A portion of this radiation is intercepted by the target and reflected back and collected by the radar antenna and delivered to a receiver, where it is processed to determine the size, position and shape of the target.

A single antenna is usually used on a time shared basis for both transmission and reception when the radar waveform is a repetitive series of pulses (pulse train). The range or distance to a target is found by measuring the time it takes for the radar signal to travel to the target and return back to the radar. The direction of the target is found from the direction of the normal beam of the radar, where the received echo signal is of maximum amplitude. If the target is in motion there is a shift in the frequency of the echo signal due to the Doppler effect. This frequency shift is proportional to the velocity of the target relative to the radar (radial velocity). This effect is used to separate moving targets from fixed background (clutter) echoes. Radar has many application fields such as military, remote sensing, weather monitoring, air traffic control, law enforcement and highway safety, ship and aircraft navigation, and space exploration.

13.2 The Range Equation:

The range to a target R is determined by the time T_R which is the round trip time for the radar pulse to travel to the target and back, where $T_R = 2R/c$, where c is the speed of light

$$R = (c\,T_R)/2 \qquad (13-1)$$

$$R\,(km) = 0.15\,T_R\;(\mu s) \qquad (13-2)$$

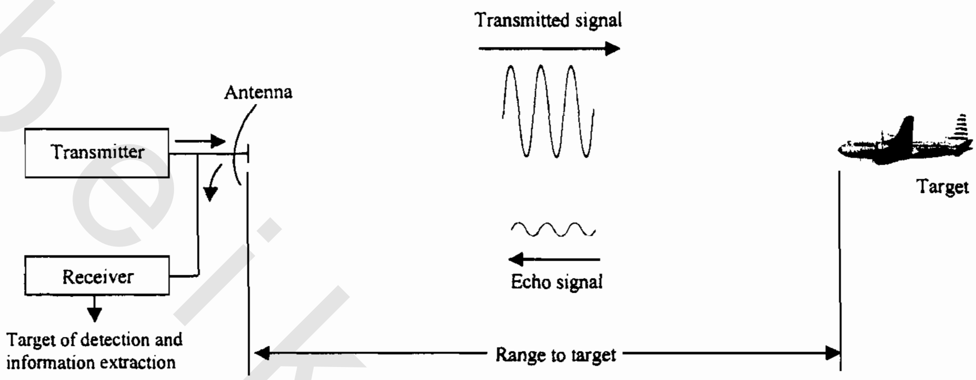


Fig. (13.1) Principle of Radar

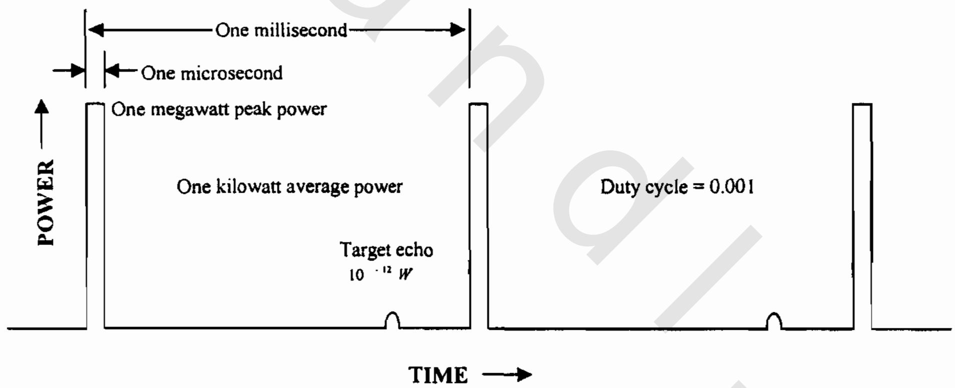


Fig. (13.2) Echo pulse

Each microsecond of round trip travel corresponds to a distance of $150\,m$. Once a signal is radiated into space by radar, sufficient time must elapse to allow for all echo signals to return to the radar before the next pulse is transmitted. The rate at which pulses may be transmitted therefore is determined by the longest range at which a target is expected before a second pulse is emitted.

If the time between pulses T_p is too short, an echo signal from an early pulse reflected from a target at the farthest detectable distance may arrive after the transmission of the next pulse, (second time around) which may be mistakenly associated with an echo signal from a near target due to the second pulse. This can result in ambiguous measurement of range. The range beyond which targets appear as second time around echoes is the maximum unambiguous range R_{un} (Fig. 14.2),

$$R_{un} = \frac{c\,T_p}{2} = \frac{c}{2f_p} \qquad (13-3)$$

where T_p is the pulse repetition period and f_p is the pulse repetition frequency. A very wide pulse is needed for some radars to achieve sufficient energy to detect small targets at long ranges. Continuous wave ($C\,W$) waveforms have also been used in radar. Since they have to receive while transmitting, $C\,W$ radars depend on Doppler frequency shift of echo signal caused by a moving target to separate in the frequency domain the weak echo signal from the large transmitted signal and the echoes from the fixed clutter as well as to measure the radial velocity of the targets, hence called moving target indicator (MTI).

The radar equation relates the range of a radar to the characteristics of the transmitter, receiver, antenna, target and the environment. If the transmitter power P_t is radiated by an isotropic antenna - one that radiates uniformly in all directions - The power density ρ_R at range R from an isotropic antenna is given by

$$\rho_R = \frac{P_t}{4\pi R^2} \qquad (13-4)$$

Directive antennas with narrow beams concentrate the radiated power P_t in a particular direction. The gain of an antenna is a measure of the increased power density radiated in some direction as compared to the power density that would appear in that direction from an isotropic antenna. The maximum gain G of an antenna is given by

$$G = \frac{\text{Maximum power density radiated by a directive antenna}}{\text{Maximum power density radiated by an isotropic antenna}}$$

Thus, the power density at the target from a directive antenna with a transmitting gain G is given by

$$\rho_R' = \frac{P_t\,G}{4\pi R^2} \qquad (13-5)$$

The target intercepts a portion of the incident energy and reradiates it in various directions. The radar cross section σ of the target determines the power density returned to the radar for a particular power density incident on the target. Reradiated power density back at the radar ρ_R'' is given by

$$\rho_R'' = \frac{P_t\, G}{4\pi R^2}\,\frac{\sigma}{4\pi R^2} \qquad (13-6)$$

The radar antenna captures only a portion of the echo signal incident on it. The power received by the radar is given as the product of the incident power density times the effective area A_e of the receiving antenna.

The effective area is related to the physical area A by the relation $A_e = \eta_a\, A$, where η_a is the antenna aperture efficiency. The received signal power is then

$$P_r = \frac{P_t\, G}{4\pi R^2}\,\frac{\sigma}{4\pi R^2}\, A_e = \frac{P_t\, G\, A_e\, \sigma}{(4\pi)^2\, R^4} \qquad (13-7)$$

The maximum unambiguous range of a radar $R_{\max}$ is the distance beyond which the target cannot be detected. It occurs when the received signal power P_r just equals the minimum detectable signal power $S_{\min}$

Thus,

$$R_{\max} = \left(\frac{P_t\, G\, A_e\, \sigma}{(4\pi)^2\, S_{\min}} \right)^{1/4} \qquad (13-8)$$

This is the fundamental form of the radar range equation. The important antenna parameters are the transmitting gain and the receiving effective area. From antenna theory

$$G = \frac{4\pi A_e}{\lambda^2} \qquad (13-9)$$

where λ is the wavelength length. Thus,

$$R_{\max} = \left[\frac{P_t G^2 \lambda^2\, \sigma}{(4\pi)^3\, S_{\min}} \right]^{1/4} \qquad (13-10)$$

$$= \left[\frac{P_t\, A_e^2\, \sigma}{4\pi\, \lambda^2\, S_{\min}} \right]^{1/4}$$

$$= \left[\frac{P_t\, \eta_a^2\, A^2\, \sigma}{4\pi\, \lambda^2\, S_{\min}} \right]^{1/4} \qquad (13-11)$$

13.3 Pulse Radar:

Fig. (13.3) shows a simple block diagram of a radar system. The radar signal is produced at low power by a waveform generator which is then inputted to a power amplifier. On transmit, the parabolic reflector focuses the energy into a narrow beam as an automobile headlight or a search light. A phased array antenna is a collection of numerous small radiating elements whose signals combine in space to produce a radiating plane wave. Using phase shifters at each of the radiating elements an electronically steered phased array can rapidly change the direction of the antenna beam in space without mechanically moving the antenna. The beam width of a parabolic reflector is roughly given by $65\lambda / D$ in degrees where D in the aperture diameter. For a complete rotation (antenna scan), the rate of 6 rpm is used for long range civil air traffic control. The duplexer allows a single antenna to be used on a time shared basis for both transmission and reception. Superheterodyne principle is used where the mixer and local oscillator convert the RF signal to an IF frequency.

The IF amplifier is designated as a matched filter which maximizes the output peak S/N, thus maximizing the detectability of a weak echo signal and attenuating unwanted signals. The IF amplifier is followed by a crystal diode traditionally called second detector or demodulator. Its purpose is to assist in the signal demodulation. The combination of IF, 2^{nd} detector and video amplifier act as an envelope detector to pass the pulse modulation (envelope) and reject the carrier frequency. The amplifier is sufficient to let the signal be seen on a CRT display. At the output of the receiver a decision is made whether or not a target is present. This decision in based on the magnitude of the receiver output. If the output is large enough to exceed a predetermined threshold the decision is that a target is present, otherwise the signal is regarded as noise. The threshold level is set so that the rate at which false alarms occur due to noise crossing the threshold is below some specified tolerable value as long as the noise remains constant for the case of dominant receiver noise. If on the other hand, the noise is external to the radar as from interference or deliberate noise (jamming) or if clutter echoes are larger than the receiver noise, the threshold has to be varied adaptively to maintain the false alarm rate at a constant value.

A radar usually integrates many echo pulses from the target to enhance S/N before the detection decision is made. A signal processor passes the desired echo signal and rejects unwanted signals or clutter. An automatic tracker is a data processor that is often used to establish the track of the target by measuring its location over a period of time.

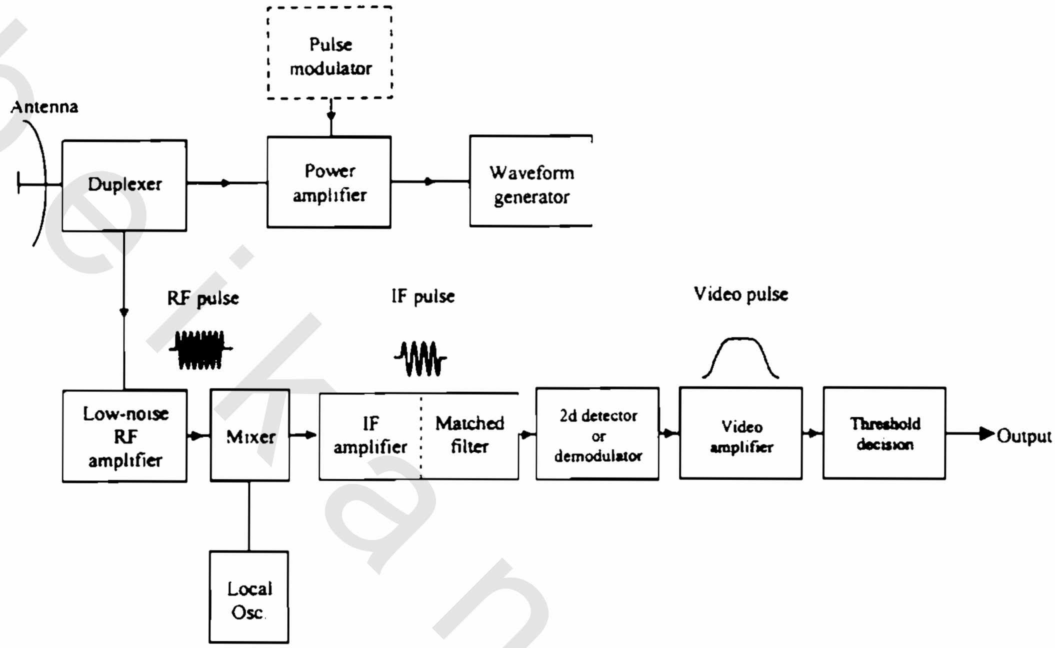


Fig. (13.3) A simple block diagram of a pulse radar

Radars can operate in different frequencies, polarizations, pulse widths , and pulse repetition frequencies. Table, (13.1) lists radar frequencies and their designations.

13.4 Doppler Radar:

The most powerful method for detecting moving targets in the midst of a large clutter is by taking advantage of the Doppler effect which is the change of frequency of the radar echo signal due to the relative velocity between the radar and the moving target.

If the range to the target is R the total number of wavelengths λ in the two way path from radar to target and return is $2R/\lambda$. Each wavelength correspond to a phase change of 2π radians. The total phase change in the two way propagation path is the

$$\phi = 2\pi \times \frac{2R}{\lambda} = \frac{4\pi R}{\lambda} \qquad (13-12)$$

Table. (13.1) Radar frequencies

Band Designation	Nominal Frequency range	Specific Frequency Ranges for Radar based on ITU Assignments in Region 2
HF	3-30 MHz	
VHF	30-300 MHz	138-144 MHz 216-225 MHz
UHF	300-1000 MHz	420-450 MHz 850-942 MHz
L	1-2 GHz	1215-1400 MHz
S	2-4 GHz	2300-2500 MHz 2700-3700 MHz
C	4-8 GHz	5250-5925 MHz
X	8-12 GHz	8500-10.680 MHz
K_u	12-18 GHz	13.4-14.0 GHz 15.7-17.7 GHz
K	18-27 GHz	24.05-24.25 GHz
K_a	27-40 GHz	33.4-36 GHz
V	40-75 GHz	59-64 GHz
W	75-110 GHz	76-81 GHz 92-100 GHz
mm	110-300 GHz	126-142 GHz 144-149 GHz 231-235 GHz 238-248 GHz

If the target is in motion relative to the radar, R is changing and so is the phase. Differentiating eqn. (13 – 12) with respect to time gives the rate of change of phase which is the angular frequency

$$\omega_d = 2\pi f_d = \frac{d\phi}{dt} = \frac{4\pi}{\lambda}\frac{dR}{dt} = \frac{4\pi}{\lambda} v_r \qquad (13-13)$$

$$f_d = \frac{2v_r}{\lambda} = \frac{2f_c v_r}{c} \qquad (13-14)$$

where $v_r = dR/dt$ is the radial velocity or rate of change of the range, with time, and f_d is the Doppler frequency shift. If the angle between the target's velocity vector and the radar line of sight is θ where v is the velocity of the target (Fig. 13.4),

$$v_r = v \cos\theta \qquad (13-15)$$

We have two types of Doppler radar; CW radar and pulse radar. The block diagram of a very simple CW radar that utilizes the Doppler frequency shift to detect moving targets is shown (Fig. 13 5a).

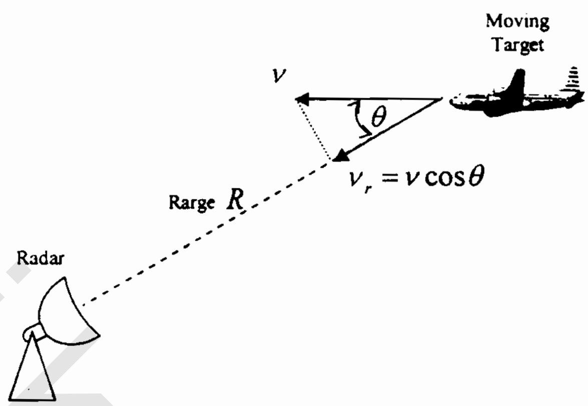
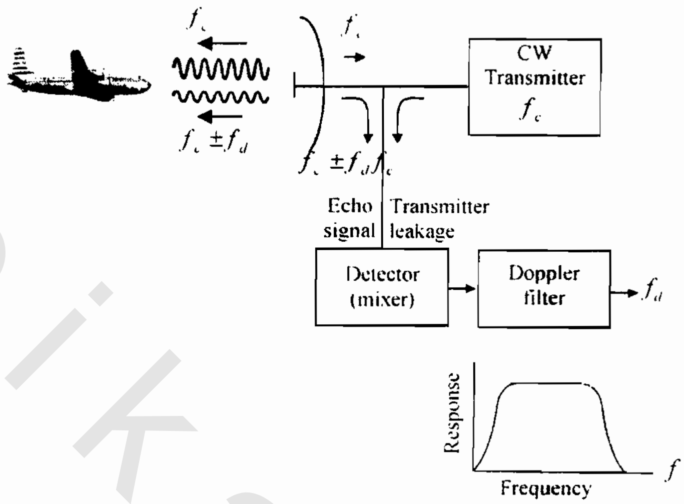


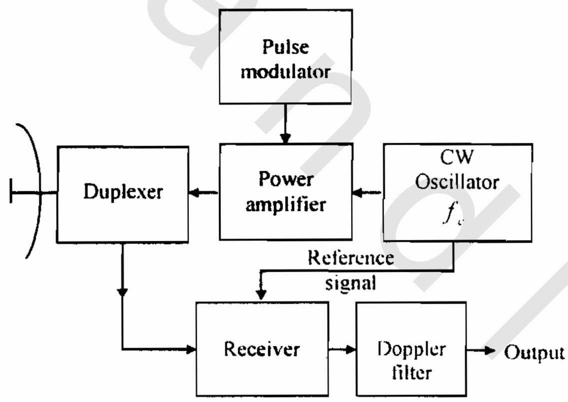
Fig. (13.4) Range of moving target

Unlike a pulse radar, a CW radar transmits while it receivers. Without the Doppler shift produced by the movement of the target, the weak CW echo would not be detected in the presence of the much stronger signal from the transmitter. Filtering is used to separate the echo from the stronger transmitter signal. The transmitter transmits unmodulated carrier at f_c which is radiated by the antenna. On reflection by a moving target, the transmitted signal frequency is shifted by $\pm f_d$ (the + sign for the closing target and the − sign for the receding target). A mixer multiplies the echo signal $(f_c \pm f_d)$ and the transmitter leakage signal (f_c) which acts as a reference. The filter allows the difference frequency to pass and rejects the sum. The Doppler filter has a lower frequency cut off such as to remove the transmitter leakage signal and the clutter echoes.

The maximum radial velocity of the moving target determines the upper cut off frequency of the filter. The problem with this kind of radar is that the sign of the Doppler shift and hence the direction of the target motion is lost. Also, pulse radar cannot be generated by simply turning on and off pulses, since the reference signal at the receiver is lost in the absence of the pulse. One way to introduce the reference signal is shown (Fig. 13.5b). The output of a stable CW oscillator is amplified and turned on and off (modulated) to generate a series of high power pulses. The received echo signal is mixed with the output of the CW oscillator, which acts as a coherent reference to allow recognition of Doppler frequency shift.



(a)



(b)

Fig. (13.5) Doppler radar

a) CW radar *b) pulse radar*

In this case, a PLL is used in which the phase detector recognizes the + and – signs of the frequency shift, hence, the target can be determined if closing or receding.

The transmitted signal is $A_c \sin(2\pi f_c t)$ and the received signal is $A_r \sin[2\pi f_c (t - \tau_R)]$, where A_c is the amplitude of the transmitted signal, and A_r is the amplitude of the received echo. The round trip time is $\tau_R = 2R/c$, where R is the range. If the target is moving toward the radar, $R = R_0 - v_r t$ where v_r is the radial velocity of the target. The received signal becomes

$$V_c' = A_r \sin\left[2\pi f_c\left(1+\frac{2v_r}{c}\right)t - \frac{4\pi f_c R_0}{c}\right] \qquad (13-16)$$

The received frequency changes by the factor

$$\frac{2f_c v_r}{c} = \frac{2v_r}{\lambda} = f_d \qquad (13-17)$$

If the target is moving away from the radar, the sign of the Doppler frequency would be minus. The output of the phase detector is

$$V_d = A_d \cos\left(2\pi f_d t - 4\pi R_0 / \lambda\right)$$

For a stationary target or clutter $f_d = 0$ and the output is constant. The echo signal from a moving target results in a time varying output which is the basis for rejecting stationary clutter. The PLL action gives an output voltage whose sign determines if the Doppler shift is positive or negative.

13.5 Pulse Compression:

A long pulse is needed for long range radars to achieve sufficient energy to detect small targets at long range. A long pulse however, has poor resolution in the range. We need very short pulses to be able to detect echo from nearby aircraft. Yet, we need a long pulse to have enough energy to propagate to distant targets and come back at a detectable signal level. This contradiction is removed by using a technique called pulse compression. Frequency or phase modulation is used to increase the spectral width of a long pulse, hence reduce the effective pulse width. Hence we increase the resolution, yet maintain the energy requirement of a long pulse. If we use directly a short duration pulse, then we will end of with a high peak power for the same large pulse energy. The transmission line that has a high peak power is subject to voltage breakdown (arc discharge).

The modulated long pulse with its increased bandwidth B is compressed by the matched filter of the receiver to a width equal to $(1/B)$. This is called pulse compression. Thus, a long pulse of width T is used to obtain the resolution of a short pulse by modulating the long pulse to obtain a bandwidth $B >> (1/T)$ and processing the modulated long pulse in a matched filter to obtain a pulse width $\tau \approx (1/B)$.

The pulse compression ratio is defined as the ratio of the long pulse width T to the compressed pulse width τ or T/τ. Hence, it equals $B\,T$

13.6 Laser Radar (LIDAR):

Laser radar (Lidar: light detection and ranging) constitute a direct extension of conventional radar techniques and operate on the same principles as microwave radars. Because they operate at much shorter wavelengths, laser radars are capable of higher accuracy and more precise resolution than microwave radars. However, they are more susceptible to atmospheric conditions. Thus, they are generally restricted to shorter ranges in the atmosphere than microwave radar. They are used in tactical range and velocity imaging, missile guidance, precise aircraft navigation and guidance, precision fire control, precision and smart bombs and remote atmospheric sensing. The modulation capabilities of microwave radar systems can be applied to laser transmitters to allow accurate target measurement. The optical resolution associated with laser systems results in a very small angular beam width.

Whereas passive infrared (IR) systems are dependent upon target emissivity and temperature characteristics, the laser radar is target reflectivity - dependent. Range and velocity measurements of stationary and moving targets allows the target to be separated from the background to yield major improvements in automatic target detection and recognition systems. Fig. (13.6) shows incoherent and coherent detection receivers. The incoherent detection receiver at optical wavelengths is similar to a video radiometer receiver (or envelope detector).

The coherent detection system has a portion of the laser signal coupled to the optical detector via a beam splitter.

13.7 Imaging Radars

Airborne and space borne radars obtain a photograph of the ground below through the transmission and reception of electromagnetic energy. The clarity of a $2D$ photograph will depend on the resolution obtained in each dimension. The X direction is perpendicular to the flight path, while the Y direction is considered to be along the flight path.

Nearly all geological and topographic maps are based on images obtained from aircraft or satellites. Imaging devices (visible and IR) detect energy that is either sunlight reflected from the terrain or from man made structures or radiated by them as a function of their temperature (passive imaging).At visible and IR wavelengths, however, the atmosphere absorbs a significant fraction of radiation even in the clear environment. In cloudy or rainy weather, the performance of visible and IR detectors is seriously impaired due to atmospheric absorption. To overcome this dependence on weather and atmospheric conditions an imaging device is needed which provides its own source (active imaging) which is not to suffer heavily due atmospheric conditions. Radar systems with wavelength $1-30cm$ fulfill both of the above requirements (all weather operation). Note, however, that radar system operating at wavelengths in the order of centimeters cannot provide the same level of detail image resolution as visible light with wavelength $10^{-5}cm$. But for all intents and purposes, radar with centimeter wavelength is quite sufficient for most practical needs for geographical and geological purposes.

Imaging radars can be divided into two categories, real array and synthetic array. In both cases, the X – direction resolution is controlled by the transmitted pulse width. Real array radars obtain the Y – direction resolution by the antenna beam width. Since the antenna beam width in each direction is inversely proportional to its length, the Y direction resolution of real array (conventional mapping imaging radars) is obtained through the use of long antennas mounted on the belly of the aircraft. The desire to use regular size airborne antennas for ground mapping led to the invention of synthetic array (aperture) radars. They may also be called synthetic aperture radar (SAR).

These radars use the transmitted pulse length for the X – direction resolution. In the Y – direction, however, SAR radars use the incremental Doppler shift of adjacent points on the ground for resolution, rather than the antenna bandwidth, hence the antenna length is irrelevant. Doppler frequency signal processing is used for Y – direction resolution and the production of real time SAR imagery.

13.8 Electronic Counter Measures (ECM)

Almost all effective weapons now employ electronic guidance devices. However, the sophistication of today's weapon systems is such that they are rendered worthless should their electronic circuits not operate correctly. As a result, it has become essential to develop electronic counter measures (ECM) systems capable of reducing the effectiveness of weapon guidance devices .The inevitable next step has been the development of electronic counter counter measures (ECCM) to try to restore the original effectiveness of the weapon sensors.

An air defense network comprises highly sensitive and accurate surveillance radar (early warning and search radar) networks with deployment of tactical weapon systems. GPS is extensively used for precise target location, and laser guided ammunition is usually used in modern warfare.

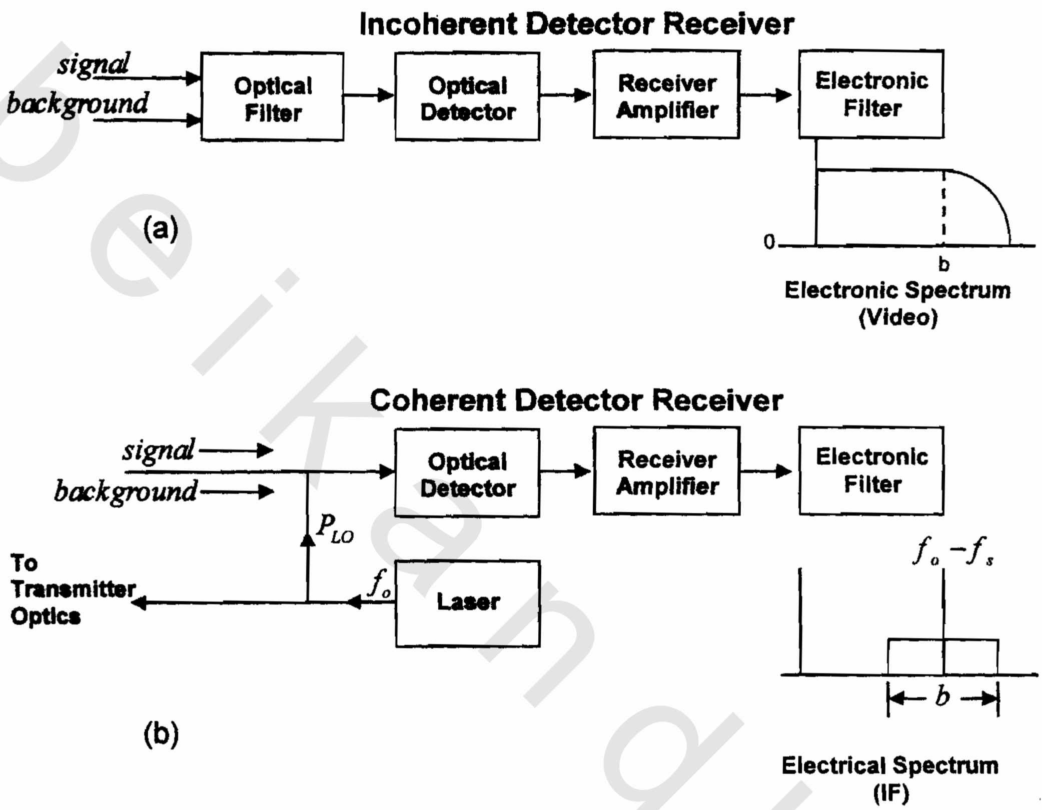


Fig. (13.6) Laser radar receiver
a) incoherent b) coherent

Surface to air missiles (SAM) systems usually consist of a local search (acquisition) radar which detects incoming threats, a process called target indication (TI) to different sensors capable of tracking them, to provide guidance to different missiles against the threatening platforms.

Unmanned air vehicles (UAV) and remotely piloted vehicles (RPV) are used for both surveillance and for guided weapon delivery. Weapon locating radar (WLR) are used to locate the source of fire. In an army command control and communication (C^3) systems have great importance.

All weapon systems depend on two phases: first the detection (search) phase and then the response (missile-artillery) phase. The functioning of all systems is based on the use of electronic sensors. Such sensors may lose their effectiveness upon jamming.

The performance of an air defense system depends on the capabilities of the long range search radar associated with it. A missile system consists of acquisition radar, a number of tracking radars, each tracking one target to supply guidance data for the missile; and a number of missile launchers. A missile may be guided exclusively by commands from the tracking radar (command missile) or it may be launched on the basis of data supplied by the tracking radar, and then acquire signals for self guidance to its target (homing). Homing can be classified as active if the missile is fitted with a sensor (seeker) comprising a small tracking radar. It may be called semi – active, if the energy source is an illuminator at the missile site and the seeker is a tracking radar receiver which detects radiation reflected by the target.

Homing is called passive if the missile has a seeker which does not require any transmitter, but detects the energy radiated by the target in the infrared, ultraviolet or microwave spectrum. Thus, all weapon system employ one of the following sensors that could be the victims of electronic jamming systems, search radar - tracking radar - RF seeker - electro optic search system-IR seeker.

Also, communication systems can be jammed, Interfering with such sensors is called soft kill in comparisen with the use of fire power which is called hard kill. Electronic warfare aims at minimizing the effectiveness of these weapon systems which depend on electronic sensing devices for their operation. Part of this war effort is the strategic knowledge of the enemy's electronic devices which is obtained by monitoring and studying the signals they emit. This is called signal intelligence (SIGINT). This may be further classified into electronic intelligence (ELINT), by collecting radar emission, and communication intelligence (COMINT) by collecting communication data.

Electronic counter measures (ECM) are then generated aiming at the maximum reduction of the operational capabilities of enemy electronic devices including search radars, acquisition and tracking radars, IR systems, laser systems and communication systems.

In addition, electronic counter counter measures (ECCM) must be adopted by eliminating intentionally caused disturbance or interference. Missiles with IR guidance do not need to radiate any RF signals because they lock on to IR emission from the target .Thus, the presence of an IR missile cannot be detected by any RF electronic equipment. In fact, their direction is normally obtained by dedicated radar. The desire to defend a platform against missile attack often conflicts with the need to keep radar turned off (radar silence) to avoid detection by the enemy.

Passive electro optic sensors are capable of detecting the aerodynamic heating or the IR radiation produced by the booster at the time of launching. The problem with these sensors is that the background IR radiation is usually much stronger than the signal produced by the missile. In tank warfare, laser range finders gives precision guidance for bombs or missiles against ground targets.

ECM aims at neutralizing hostile electronic systems that have been detected by concealing the platform to be protected, or deceiving the hostile weapon system may otherwise be deceived by creating spurious targets. One of these spurious targets is called chaff. A chaff system comprises a launcher that ejects cartridges (conductive metal foil strip dipoles) within a certain distance from the protected platform and disperse a multitude of tiny dipoles which produce a cloud reflecting radar signals. Hence, the radar system is blinded.

Another method for deceiving radar is by using stealth techniques. A drastic reduction of the strength of the reflected radar signal is achieved by reducing the target radar cross section, making an aircraft for example invisible to radar.

Another way to deceive radars is to use noise jammers. Thus, the signal produced by the platform is drowned in noise. Still another method is to use a deception jammer in which a false radar target is generated. This means tracking and locking onto weapon systems shifted onto a false target. Decoys may also be used to deceive radars. A decoy may be passive (reflectors) or active by retuning an amplified radar signal.

There are IR counter measures which prevent IR guided missiles from reaching the target. There are two types: on - board and off - board. The off - board system is a flare dispenser which is a launcher capable of ejecting cartridges that generate an intense IR radiation to deceive the missile heat seeker. The on - board type is composed of modulated IR transmitters. An AM modulated IR signal can introduce huge errors into a missile trajectory. To counteract lasers, either jammers are used as above or a cloud of smoke is dispensed to reduce visibility.

ECM-COM is meant to disturb the enemy's communication systems by producing noise signals or interference. In the midst of all this, ECCM systems are designed to operate in an electronically hostile environment, i.e., in the presence of intentional jammers with minimal reduction of their own capabilities.

This is the name of the game in electronic warfare, measures and counter measures and counter counter measures and the saga goes on.

Problems

1. In a pulse radar, the peak power is $1nW$,pulse width $\tau = 1\mu s$ and pulse repetition period $T_p = 1ms$. Find the maximum unambiguous range, the average power and the energy of the pulse?

2. Calculate the distance between two equal targets which can be recognized as being resolved in range for the above problem?

3. At frequency $3GHz$ and beam width 2°, calculate the antenna size. $\tau = 1\mu s$, $T_p = 1ms$. How many pulses are emitted in one revolution?

4. Compare R_{max} for $S_{min} = 1\mu W$ to the case when $S_{min} = 100nW$?

5. A radar has pulse width 1 μs and $1MW$ peak power. Find the energy per pulse and the range. Find also the limit of resolution for nearby targets?

6. If it is desired to have a resolution of 15 cm, what is the width and the new peak power to maintain the same pulse energy?

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