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Research Paper

A Comprehensive Review of Radar System Technology

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ABSTRACT: *Our ability to align with the trend of innovations in science and technology will not only emancipate ignorance but also unfold our ability to evaluate, understand and predicate possibilities in our society, environment and the world at large. Radar system technology gives us the privilege to achieve the above-mentioned fact. The word Radar is an acronym for Radio Detection and Ranging. It is a means of getting information about a distant target, by sending electromagnetic waves to them and analysing the echoes from the target to generate relevant reports about the target. This paper seeks to x-ray the applications of radar technology in every sphere of human life, derivation of the basic radar equations for monstatic radar case and bistaic radar case, the effect of losses on the derived radar equations and the extraction of six relevant information about the target from the received radar echo signal. The advantages and limitations of continuous wave (c-w) radar and Pulse radar systems were also highlighted.*

KEYWORDS: *Amplitude, Clutter, Echo, Phase,Target,*

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I. INTRODUCTION

The word Radar is an acronym for Radio Detection and Ranging. A Radar system uses radio waves to detect the presence of a target and to determine its range and speed. The system comprises simply of a radio transmitter which emits electromagnetic radiation which when interrupted by any object such as a ship or mountain is partially reflected back to the radio receiver located near the transmitter. The reflection is called an "echo", and the reflecting object is called a "target". The presence of an echo signal indicates that a target has been detected, the echo is referred to as a "target signal", if however, the echo comes from an unwanted target which makes it difficult to reflect the desired target. The unwanted target is known as "Clutter"[1]. Figure 1 shows some typical radar Installations.

Figure 1: Radar Installations

A radar system generally consists of a transmitter which is made up of a Driver, Modulator and Oscillator as shown in Figure 2. A radar transmitter produces an electromagnetic signal which is radiated into space by an antenna. When this signal strikes any object, it gets reflected or reradiated in many directions. This reflected or echo signal is received by the radar antenna which delivers it to the receiver, where it is processed to determine the geographical statistics of the object. The range is determined by calculating the time taken for the signal to travel from the radar system to the target and back to the radar system.

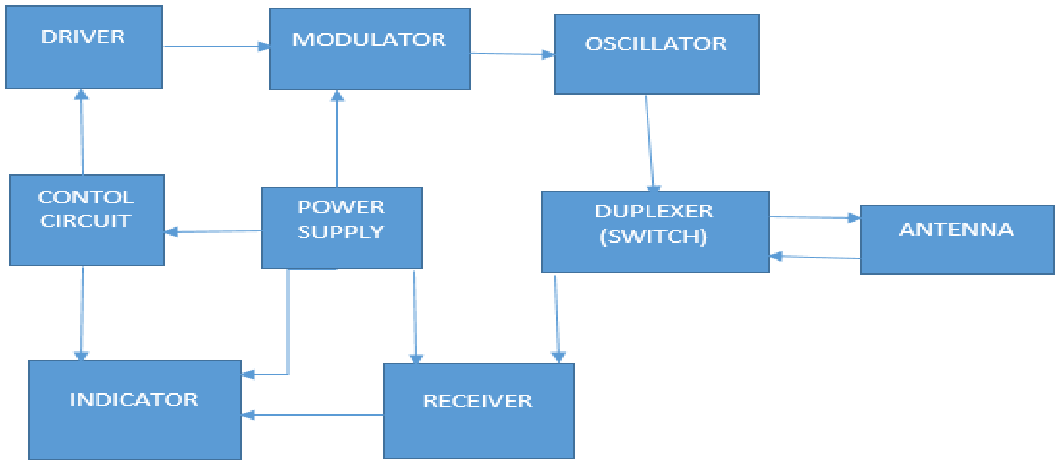

Figure 2: Block Diagram of a Basic Radar system.

For a radar transmitter running continuously, the returning echoes from the target will also be received continuously and will with time be indistinguishable leading to ambiguity in range determination. For this reason, a common practice is to pulse modulate the radar transmitter i.e, the RF energy is emitted in short, high-power pulses. The echoes are then received in short pulses also because the transmitter is always off during reception (Duplex operation).With this operation, it is possible to associate a given echo signal with a specific transmitted pulse and so determine the range unambiguously. Radar using pulse modulation is the most common type and it is called “Pulse Radar”[1].

One of the main characteristics that define an electromagnetic field (EMF) is its frequency or its corresponding wavelength. Fields of different frequencies interact with the body in different ways. One can imagine electromagnetic waves as series of very regular waves that travel at an enormous speed, the speed of light. The frequency simply describes the number of oscillations or cycles per second, while the term wavelength describes the distance between one wave and the next. Hence wavelength and frequency are inseparably intertwined: the higher the frequency the shorter the wavelength[2]. During World War II, Radar frequencies were given letter designations which have stuck since then even though the exact frequency limits of the designated band are not well delineated. The frequencies near10GHz are termed X-band,those near 6GHz are called C-band while those near 3GHz are referred to as S-band. Frequencies in the region of 1GHz are termed L- band, 2GHz is sometimes classified as S-band and sometimes as L-band. Other frequently used designations are Ku – band for frequencies around 18GHz, K- band for 25GHz and Ka- band for frequencies in the region of 35GHz [1].

II. APPLICATION OF RADAR SYSTEM TECHNOLGY

The first observation of the radar effect at the U.S. Naval Research Laboratory (NRL) in Washington, D.C., was made in 1922. NRL researchers positioned a radio transmitter on one shore of the Potomac River and a receiver on the other. A ship sailing on the river unexpectedly caused fluctuations in the intensity of the received electromagnetic radio signals when it passed between the transmitter and receiver. (Today such a configuration would be called bistatic radar). The uses of radar systems cannot be over-emphasized, but for the sake of this paper, we shall list the applications of Radar Technology as follows: Civilian Applications, Military Applications and Scientific Applications.

2.1 Civilian Application of Radar System Technology

The major areas of civilian application are briefly discussed below.

2.1.1 Air Traffic Control (ATC)

Radar is employed throughout the world for the purpose of safely controlling air traffic, en-route and in the vicinity of airports. Aircraft and ground vehicular traffic at large airports are monitored by means of high-resolution radar. Radar has been used with Ground Control Approach (GCA) system to guide aircraft to a safe landing. Infrastructure like the Controller-pilot Data Link Communication (CPDLC) and Automatic Dependent Surveillance-Broadcast (ADSB) help to facilitate absolute utilization of domestic airports at night

2.1.2 Ship Safety

Radar is used in enchaining the safety of ship travel warning of a potential collision with other ships, and detecting navigation buoys, especially in bad vicinity. In terms of numbers, this is one of the largest applications of radar system. But in terms of physical size and cost, it is one of the smallest. It has also been proven as one of the most reliable Radar systems. Shore-base Radar of moderately high resolution is also used for the surveillance of habour as an aid to navigation of a ship. Automatic Identification System (AIS) is a system used by ships and vessels for identification at sea. AIS helps to resolve the difficulty of identifying ships when not in sight (e.g. at night, in radar blind arcs or shadows or at distance) by providing ID, position, course, speed and other ship data with all other nearby ships.

2.1.3 Air Craft Navigation

The weather avoidance radar is used on air craft to outline regions of precipitation to the pilot is a classical form of radar. Radar is also used for terrains avoidance and terrain following.Sometimes ground mapping radars of moderately high resolution are used for aircraft navigation purposes

2.2 Military Application of Radar system Technology

A large number of civilian applications of radar listed above also apply to the military, especially radar navigation. Other applications by the military are surveillance, control of weapons and law enforcement.

2.2.1Surveillance Radar

Surveillance Radar is used for the detection and location of hostile targets for the purpose of taking proper military actions. Examples of such radars are Distance Early Warning (DEW) Radar for aircraft detection, Ballistic Missile Early Warning System (BMEWS) Radar for detection and tracking of International ballistic missiles, the long-range search radar for the SACE system (shipborne surveillance radar) and Airborne Early Warning (AEW) radar.

2.2.2 Weapon Control Radar

Weapon Control Radar include accusation radar and tracking radar for air deface system, homing radars in guided missile, AI (Airborne Interception) Radar to guide a fighter Aircraft to its target, Bombing Radar.

2.2.3 Law Enforcement

In addition to the wide use of radar to measure the speed of automobile traffic by highway police, radar has also been employed as a means for the detection of intruders. Infrared wireless communication communicates information in a device or system through Infra- Red (IR) radiation. IR is electromagnetic energy at a wavelength that is longer than that of red light. It is used for security control, TV remote control and short-range communications. In the electromagnetic spectrum, IR radiation lies between microwaves and visible light. So, they can be used as a source of communication [3]

2.3 Scientific Application of Radar System Technology

Radar has been used as a measurement tool by research scientists and this has vastly increased our knowledge of metrology. Radar can guide space vehicles and satellites used for exploration of interplanetary space

2.3.1. Space.

Space vehicles have used radar for docking and for landing on the moon some of the largest ground-based radars are for the detection and tracking of satellites. Satellite-borne radars have also been used for remote sensing. NigeriaSat-1 can image scenes as large as 640 x 560 km, providing unparalleled wide-area, medium-resolution data which is used within Nigeria to monitor pollution, give early warning signals of environmental disaster, help detect and control desertification in the northern part of Nigeria; assist in demographic planning; establish the relationship between vectors and the environment that breeds malaria, give early warning signals on future outbreaks of meningitis using remote sensing technology; provide the technology needed to bring education to all parts of the country through distant learning, and to aid in conflict resolution and border disputes by mapping out state and International borders [4].

2.3.2. Remote Sensing.

All radars are remote sensors, however, as this term is used it implies the sensing of geophysical objects or the environment. Sometimes, radar has been used as a remote sensor of the weather. It has also been used in the past to probe the moon and the planet (Radar Astronomy) remote sensing with radar is also concerned with health resources, which includes the measurement and mapping of sea condition, water resources, ice cover, agriculture, forestry condition, geological formation and environmental pollution.

2.3.3. Medicine.

Radar is also used in the medical profession for the measurement of x-ray and ultra scan system.

III. BASIC RADAR EQUATIONS

If Pt is the Power of the transmitting antenna, Pr is the Power of the Receiving antenna, Gt is the gain of the transmitting antenna, Gr is the gain of the Receiving antenna, Rt is the distance from the transmitter to the target, Rr is the distance from the target to the receiver, σ is the target cross-section area or the scattering coefficient of the target, Ae is the effective aperture (area) of the receiving antenna and λ is the transmitted wavelength. Then the basic Radar equation is mathematically expressed as follows

3.1 Monstatic Radar Case

A monostatic radar is a radar system that uses one antenna for both transmitting and receiving of radar signals. This operation is made possible by the use of a duplexer (switch) as shown in Figure 3.

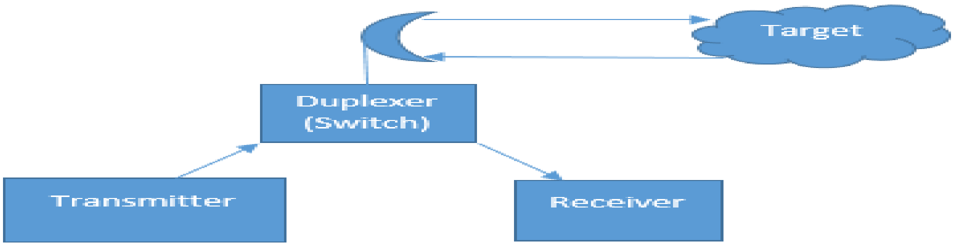

Figure 3: Monostatic Radar system

In MonoStatic Radars, the same antenna is used for transmission and reception.
Thus,

$$G_t = G_r = G \qquad (1)$$
$$R_t = R_r = R \qquad (2)$$

Therefore, from first principle, Pr is expressed mathematically as

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \qquad (3)$$

From antenna theory, the gain of an antenna is related to the effective capture area of the antenna by this expression [1].

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

Therefore, the basic radar equation is expressed as

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} = \frac{P_t A_e^2 \sigma}{4\pi \lambda^2 R^4} \qquad (5)$$

where

Pt = transmitter power
G = Gain of the Antenna
Ae = effective aperture (area) of the receiving antenna
λ = transmitted wavelength
σ = radar cross section area, or scattering coefficient, of the target
R = distance from the transmitter to the target or distance from the target to the receiver.

From equation 5 we can predict the range for a monostatic radar case as follows:

$$R = \left[\frac{P_t A_e^2 \sigma}{P_r 4\pi \lambda^2}\right]^{\frac{1}{4}} = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_r}\right]^{\frac{1}{4}} \qquad (6)$$

From equation 6, the target Range R varies as the fourth root of the transmitted power. Thus, all other factors being equal, it is necessary to multiply the transmitted power by a factor of 16 in order to double the range. However, it is only necessary to multiply the antenna area or gain by a factor of 4 to accomplish the same thing. Increasing the frequency (i.e reducing the wavelength) is another way to increase the range R.

From the foregoing equations for range R, the maximum Radar range R_{max} beyond which the target can no longer be detected is readily determined. This occurs when the received echo signal power just equals the minimum detectable signal power called (S_{min}) for the receiver (depends on the receiver sensitivity)

$$R_{max} = \left[\frac{P_t A_e^2 \sigma}{S_{min} 4\pi\lambda^2}\right]^{\frac{1}{4}} = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min}}\right]^{\frac{1}{4}} \qquad (7)$$

Equation 7 is the basic radar equation that defines the maximum range performance(R_{max}) for a monostatic radar system.

3.2 Bistatic Radar Case

A bistatic radar has two separate antennas, one for transmitting and the other for receiving as opposed to a monostatic radar which uses one antenna for both functions. The term bistatic however is usually applied to a system in which the transmitter and Receiver are widely separated as well as having separate antennas. The target distance (range) from transmitter and receiver are different as shown in figure 4 and equation 9.

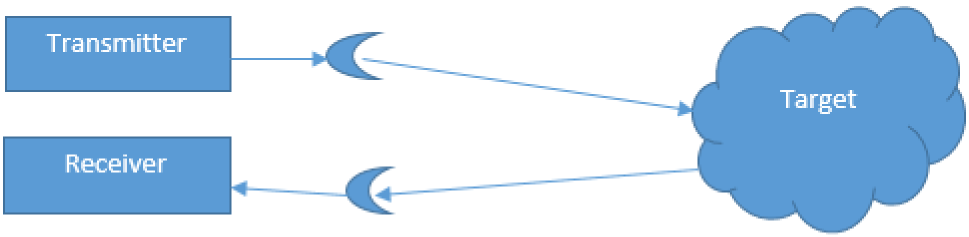

Figure 4 : Bistatic Radar system

In general, the form of radar equation for bistatic radar is in general different from that of monostatic radar and the following expression is readily derived for the receiced power in the bistatic case

$$Gt \neq Gr \qquad (8)$$

$$R_t \neq R_r \qquad (9)$$

Recall from equation 5 above, for a bistatic case, the received power is expressed as follows:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_t^2 R_r^2} = \frac{P_t A_e^2 \sigma}{4\pi\lambda^2 R_t^2 R_r^2} \qquad (10)$$

where

Pt = transmitter power
Gt = Gain of the Transmitting Antenna
Gr = Gain of the Receiving Antenna
Ae = effective aperture (area) of the receiving antenna
λ = transmitted wavelength
σ = radar cross section area, or scattering coefficient, of the target
Rt = distance from the transmitter to the target
Rr = distance from the target to the receiver.

3.3 Radar System Losses

The achievable maximum range in any practical radar system is always substantially less than that calculated by Using the (monostatic) radar equation. In fact, the practical range turns out to be at most one-half of the predicted range. This is mainly due to the various systems losses which have been neglected in the derivation. The overall loss is called the Radar System loss and is the sum of all the losses expressed in dB [5].

3.3.1 Radio Frequency (RF) Transmisssion Line Loss

Attenuation due to the waveguides, coaxial line and other components in the system. These components include directional couplers, duplexers, filters etc all of which have small but finite attenuation. Furthermore, if the antenna is mismatched to free space or to the transmitter (receiver) there will be additional loss due to reflection. The loss due to mismatch is usually considered to be a part of the transmission line losses.

3.3.2 Propagation Loss

Attenuation of signals during propagation in space, including the effects of atmospheric absorption and reflection, as well as ground reflection and multipath transmission.

3.3.3 Operator Loss

This is a measure of operators' efficiency. A trained operator can recognize a weak signal more than an untrained operator but even then a trained operator will miss a weak signal when he is tired or under pressure or stress.

If the effect of the system loss is included in the radar equation, the equation will give a more accurate picture of the practical achievable range. A system loss factor is placed in the denominator of the monostatic radar equation thus

$$R_{max} = \left[\frac{P_t A_e^2 \sigma}{S_{min} 4\pi \lambda^2 L}\right]^{\frac{1}{4}} = \left[\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{min} L}\right]^{\frac{1}{4}} \quad (11)$$

Where L is a number (greater than unity) equivalent to the system loss in decibels.

Other sources of losses arethe statistical or unpredictable nature of several of the parameters in equation 11. For example, both σ and S_{min} are statistical in nature. The equation also does not account for other statistical factors such as meterological conditions along the propagation path [5].

IV. EXTRACTION OF INFORMATION FROM RADAR SIGNALS

When the electromagnetic (e-m) wave from a radar transmitter hits a target, three things happen;

(i) A portion of the e-m wave is absorted by the target and converted to heat
(ii) A portion of the e-m wave is reflected while
(iii) A portion of the e-m wave is scattered in many directions , with some of the e-m wave traveling back towards the radar receiver.

Once a radar target has been detected, the data gathered from the received signal can be used to extract information about the following characteristics of the target:

- Target Range
- Target Range Rate (Speed)
- Target Angle of Arrival in elevation or Azimuth (Angular direction)
- Target Size
- Target Shape
- Target Change of Shape (Rotation)

The source of target information in a radar system is the electromagnetic radiation scattered by the target in the direction of the radar receiver. The scattered signal at any point in space may be resolved into its spectral (frequency) components at a given time, each frequency component can be regarded as having an amplitude and a phase (That is Fourier decomposition of the signal). By observing a series of amplitude and phase values as a function of time, frequency and position, Six possible first partial derivatives can be obtained from which the nature of the target can be obtained [5].

4.1 Information from Amplitude Variations

- The variation of amplitude with position when frequency and time are kept constant gives an extimation of the target shape.
  That is,

$$\frac{dA}{dx}_{t,f\ are\ constant} = Target\ Shape \quad (12)$$

where

A = Amplitude
x = Position
t = Time
f = Frequency

- The variation of amplitude with frequency when Postion and time are kept constant gives an extimation of the target size.
  That is,

$$\frac{dA}{df}_{t,x\,are\,constant} = Target\ Size \qquad (13)$$

- The variation of amplitude with time when Postion and frequency are kept constant gives an extimation of the target rotation.
  That is,

$$\frac{dA}{dt}_{f,x\,are\,constant} = Target\ Rotation \qquad (14)$$

4.2 Information from Phase Variations

- The variation of Phase with Postion when time and frequency are kept constant gives an extimation of the target angular direction.
  That is

$$\frac{d\emptyset}{dx}_{f,t\,are\,constant} = Angular\ Direction \qquad (15)$$

where

$\emptyset$ = Phase
x = Position
t = Time
f = Frequency

- The variation of Phase with Frequency when time and position are kept constant gives an extimation of the target range.
  That is

$$\frac{d\emptyset}{df}_{x,t\,are\,constant} = Target\ Range \qquad (16)$$

- The variation of Phase with time when time and frequency are kept constant gives an extimation of the target speed.
  That is

$$\frac{d\emptyset}{dt}_{x,f\,are\,constant} = Target\ Speed \qquad (17)$$

Not all radars utilizes the information avalible from the entire six derivative (equation 12 to equation 17). Most radar system extract only the phase variations (Speed,Range and Angular direction) .

V. RADAR DOPPLER EFFECT

A continuous wave (c-w) radar is a radar system in which the radar transmitter is operated continuously rather than Pulsed; espectially if the strong transmitted signal can be isolated from the weak echo signal. The transmitted signal may be modulated or unmodulated.The use of separate antenna for transmitting and receiving helps to segregate the weak received echo from the strong leakage signal from the transmitter. When relative motion exists between the radar set and the target, the echo signal frequency will differ from the transmitted signal frequency, the difference in the two frequencies is referred to as the Doppler shift. This shift is used not only to detect the presence of a target but also to determine the speed at which it is moving relative to the radar set. Furthermore, the Doppler principle does not require extremely large isolation between the transmitter and receiver. The Doppler effect is the main basis of c-w radar for estimating target speed.

4.1 Advantages of c-w radar

i Equipment for detection of targets at short and intermediate ranges is simpler that for pulse radar.

ii Peak power required is less than that for pulse radar due to unity (100%) duty cycle. This, electrical breakdown as a result of high peak power is not a problem as in pulse radar. Average transmitted power is however comparable to that in the pulse case for equivalent detection capability.

iii. Continuous wave (c-w) radar transmitters are generally smaller in size and weigh about 25%-50% the weight of an equivalent pulse radar system.

iv. Continuous wave(c-w) radar readily permits discrimination between moving and stationary targets.

4.2 Limitations of c-w radar

i Continuous wave (c-w) radar cannot be used to determine target range as in the case of pulse radar due to the narrowness of the signal bandwidth. In order to overcome this limitation, one may use Frequency Modulation (FM) of the carrier to increased transmitted signal bandwidth. Thus FM-CW radar has range determination capability that the simple c-w radar does not have. Such FM-CW radar is often used for determination capability that the simple c-w radar does not have. Such FM-CW radar is often used for determination of aircraft altitude.

ii. Continuous wave (c-w) radar is usually good for detecting the presence of a single target and lacks the range resolution for two or more targets.

iii. Some limitation is imposed on the amount of power that can be transmitted especially in the monostatic situation due to the simultaneous transmit and receive operation and the possibility of leakage. There is no such limitation in the pulse radar case.

iv. Continuous wave (c-w) radar may be blind to targets at small relative velocity for which the Doppler shift may be too small to be measured.

Note that the advantages and limitations of c-w radars are , logically , the limitation and advantages respectively of pulsr radar.

VI. CONCLUSION

Radar Syatem Technology is a way of getting information about a distant target, by means of sending electromagnetic waves to them and analysing the echoes from the target to generate relevant reports about the target. This research work was able to x-ray the applications of radar technology in every sphere of human life, derivation of the basic radar equations for monstatic radar case and bistaic radar case, the effect of losses on the derived radar equations and the extraction of six relevant information about the target from the received radar echo signal. The advantages and limitations of continuous wave (c-w) radar and Pulse radar systems were also highlighted in this work.

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