Radar in the Electrical Engineering Major

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INTRODUCTION

A very important application of antennas and propagation, digital signal processing (DSP), electronics, and computer architecture is **R**adio **D**etecting **A**nd **R**anging, or RADAR. Radar is multi-disciplinary system that uses concepts and techniques from every aspect of the electrical engineering (EE) major, which is why there is no one course called "Radar" in the curriculum. In fact, one could think of each course in the EE curriculum as a radar course making up a subset of a radar system.

The purpose of this paper is twofold: to inform the EE major of how their courses relate to a radar system and to serve as a system-level overview (that means easy and interesting reading) of radar for the EE major. A list of radar-related topics taught in select courses can be found in the Appendix. Feel free to discuss with your instructors the relevance of your course material to radar systems, as it will enrich your understanding of the course material.

BACKGROUND

Radar was developed during WWII and has proliferated the civilian and military sectors for surveillance and tracking of airborne and surface targets. Some examples of airborne targets include aircraft, missiles, baseballs, asteroids, etc. Surface targets might include ships, tanks, mountains, and automobiles (anti-collision radar). Ground-penetrating radar is used to detect underground or undersea targets, such as mines, bunkers, submarines, etc. Can you think of at least three other examples of airborne, surface, and under-surface targets? The operational concept of radar is pretty simple. A transmitted signal "bounces" (reflects) off of a target and a receiver receives that reflected signal. The following text will provide a system-level discussion of the principles of radar in more detail. After studying this paper, you will be able to determine:

1. the distance to or range of a target,
2. the maximum pulse repetition rate (PRI) for a given range,
3. the maximum unambiguous range for a given PRI,
4. the maximum pulse width for a given range resolution,
5. the maximum range based on signal to noise ratio,
6. and the speed of a target based on Doppler shift.

FUNDEMENTAL BUILDING BLOCKS OF RADAR

Figure 1 shows a simple block diagram of a typical radar system, showing an antenna, a receiver (RX), a transmitter (TX), a TX/RX switch, a control/processor/storage unit, a power supply, and a display. Let's discuss each in more detail.

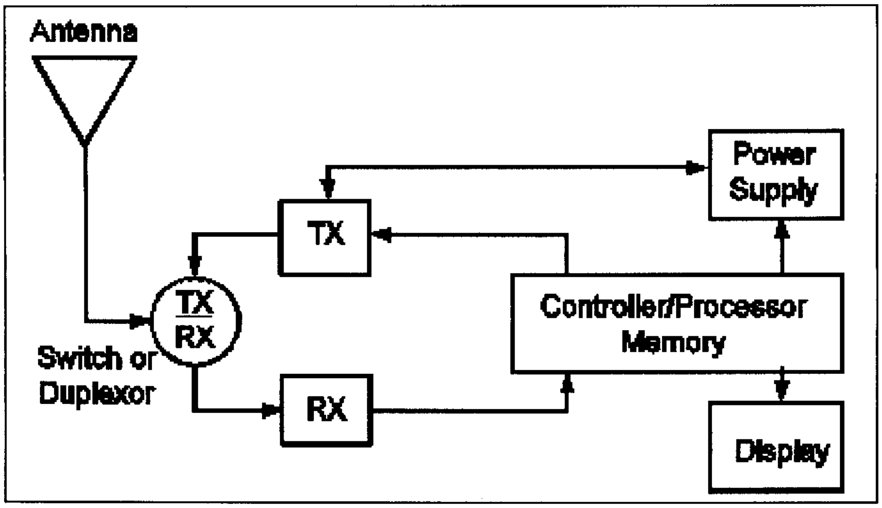

Figure 1. *Simple block diagram of typical radar system.*

RADAR RECEIVER (RX)

All radars have receivers (RX) that incorporate modulation and detection techniques learned in **EE447** (Communications I). In fact, a radar receiver is much like a digital communications receiver. The receiver receives a signal from a receiving antenna, which you studied in **EE343** (Electromagnetics) usually in the form of pulses. In that sence, you can think of a typical radar signal as *pulse modulation*. The receiver filters out the desired signal from the unwanted interfering signals and electrical noise using various techniques that you learned in **EE332** (analog filters), **EE434** (DSP), and **EE447** (matched filters). Next, the receiver *demodulates* the signal to a convenient frequency or *intermediate frequency* (IF), and then *detects* the pulses reflected from the target. There is a great deal of information contained in this string of pulses at the output of the receiver. The Controller/Processor deciphers information contained in the time at which the pulse was received, the frequency of the pulse, the pulse repetition interval (PRI), the pulse width, etc. Your DSP knowledge from **EE434** course is invaluable in this regard.

The frequency, PRI, and pulse width of the incoming pulse are used to determine if the signal is the desired radar signal as opposed to an interfering signal or just electrical noise. The receiver rejects signals that do not have the appropriate signal parameters. This can be accomplished by using matched filters (**EE447**) as well as other DSP (**EE434**) techniques. Discuss with your instructors how other signal parameters that you are learning about might be useful to the radar receiver.

RADAR TRANSMITTER (TX)

Now that we've discussed the reception of a radar signal, let's discuss how the radar signal is generated. Obviously, we need a transmitter, which at the minimum would include an oscillator, amplifier **(EE322)** and an antenna **(EE343, EE444)**. But what might not be obvious is that the radar's transmitter might not even belong to the radar system. Most radar systems are "monostatic" radars. This means that the transmitter and receiver are collocated. In fact, most radar systems share the same antenna for transmitting and receiving, as is the case in Figure 1. However, a clever means of detecting hostile targets is "bistatic" radar, which uses transmit and receive antennas that are separated by distances of many kilometers. The advantage of bistatic radar is that the transmitter, which acts as a beacon, does not give away the location of the receiver. An even more covert bistatic radar uses signals that are already reflecting off of the target from other sources that do not belong to the radar system itself. This is called uncooperative bistatic radar. An example of a transmitter that can inadvertently act as a bistatic radar transmitter is a commercial broadcast signal, such as radio or television. In the case of monostatic radar, a hostile foe can detect a radar's transmissions, jam them, and even attempt to destroy the radar transmitter. Since uncooperative bistatic radar uses passive detection, nothing is emitted by the radar to alert the foe that they are being tracked and targeted, so there is nothing for them to jam or shoot. Can you list three other signal sources that can act as a transmitter for bistatic radar?

TX/RX SWITCH

The purpose of the transmitter/receiver (TX/RX) switch is simple. The pulsed radar works by transmitting a short pulse through an antenna, then shutting off and waiting for a faint echo to return through the antenna to a very sensitive receiver. If the receiver were connected to the transmitter during transmission, the high power transmission could destroy the receiver. Therefore, the switch is synchronized to connect the antenna to the transmitter during the transmission phase, then to the receiver during the receive phase.

DUPLEXER

Some radar systems use a duplexer instead of a switch to isolate the transmitter from the receiver. This device performs the same function without actually "throwing" a switch. It incorporates a directional coupler that allows power to flow in only one direction. The duplexer routes the transmitted signal from the transmitter to the antenna and the received signal from the antenna to the receiver.

ANTENNAS

Antennas and propagation are studied in **EE343** and **EE444**. The following text will supplement your knowledge from these courses by specifically discussing radar signal propagation and characterization.

RADAR RANGE

The elapsed time between sending the pulse and receiving its echo determines the range of the target. If t is the elapsed round-trip time for the signal to travel to the target, reflect from it, and then return to the radar receiver, then the range to the target is

$$R = \frac{ct}{2} \tag{1}$$

where c is the speed of light. It takes half the round-trip time for the transmitted signal to travel the distance, R.

MAXIMUM UNAMBIGUOUS RANGE

The pulse repetition interval (PRI) determines the maximum unambiguous range. The radar periodically sends out a pulse, waits for a return, sends out the next pulse, and so on. The period between pulses is called the PRI. Often times the term pulse repetition frequency (PRF) is used, but remember that period is just the reciprocal of frequency, so

$$PRI = \frac{1}{PRF} \tag{2}$$

If a reflected signal returns from a target after the next pulse is transmitted by the radar, the receiver will associate this reflected radar return with the latest transmitted pulse, even though it came from a previous pulse. It will interpret the range or distance from the radar much less than it actually is. Therefore, it is important to be able to calculate the maximum unambiguous range. The pulse can travel $R = c \times PRI$ between each pulse. Since the pulse has to make a round trip within the PRI, the maximum unambiguous range is

$$R_{\max} = \frac{c(PRI)}{2} \tag{3}$$

Example 1 Maximum Unambiguous Range

Determine the maximum unambiguous range of a radar with a PRI of $667\mu s$.

Given: $PRI = 667\mu s$

$c = 3\times10^{8}\frac{m}{s}$ is the speed of light

Find: $R_{\max}$

Solution: $$R_{\max} = \frac{3\times10^{8}\frac{m}{s}\times667\times10^{-6}s}{2} = 10^{5}m$$

Answer: $R_{\max} = 100km$

RANGE RESOLUTION

The range resolution refers to the ability for the radar receiver to discriminate between two targets at different ranges. Therefore, this ability is limited by the time duration that each pulse is on, known as the pulse width τ. The wider the pulse, the more energy is in the received signal making it easier to detect. However, the wider pulse causes less resolution in range information. If the rising edge of the pulse from a second target reaches the receiver before the falling edge of the first pulse as in Figure 2a,b, it would appear to widen the original pulse, as in Figure 2c. The wider pulse might alert the radar receiver that multiple targets have been detected, but without knowing exactly when the second pulse began, the radar could not tell the exact range of the second pulse. In order to separate these two pulses, the pulse width must be less than

$$\tau = \frac{2(\Delta R)}{c} \tag{4}$$

where ΔR is the range resolution. This can be understood by realizing that the pulse from the second target returning at t_2 must return after the completion of the first pulse at $t_1 + \tau$, or

$$t_2 > t_1 + \tau \tag{5}$$

where τ is the pulse duration or pulse width. Substituting the elapsed time in equation 1 for each target at distances R_1 and R_2, equation 5 becomes

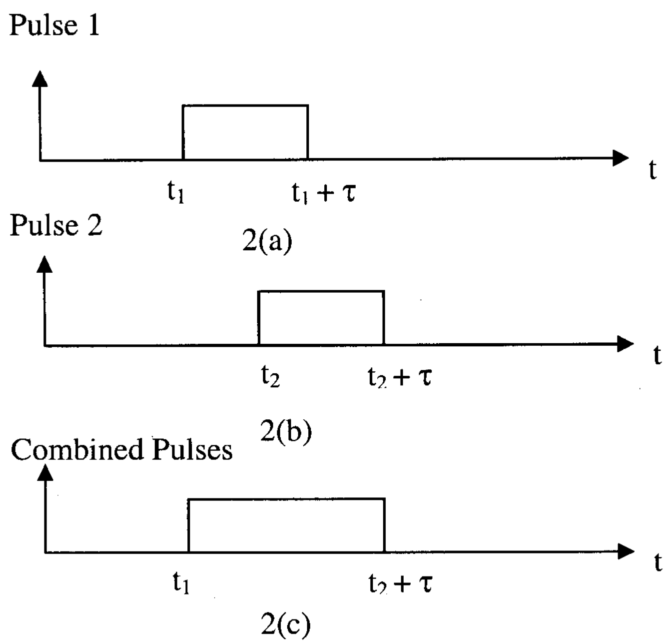

Figure 2 *Two pulses of slightly different ranges merged due to pulse width.*

$$\frac{2R_2}{c} > \frac{2R_1}{c} + \tau \tag{6}$$

Re-arranging slightly,

$$\frac{2}{c}\left(R_2 - R_1\right) > \tau \tag{7}$$

or

$$\Delta R = \frac{c\tau}{2} \tag{8}$$

where $\Delta R = R_2 - R_1$ is the range resolution or minimum discernable range between two targets, and τ is the pulse width.

Example 2 Range Resolution

In order to detect two separate targets 25 meters apart, determine the maximum pulse width.

Given: $\Delta R = 25m$

$c = 3\times10^8 \frac{m}{s}$ is the speed of light

Find: $\tau_{\max}$

Pulse 1

Solution: $\tau = \frac{2\Delta R}{c} = \frac{2(25m)}{3\times10^{8}\frac{m}{s}} = 1.67\times10^{-7}s = 167ns$

Answer: $\tau = 167ns$

Another limiting factor that determines the maximum pulse width is the minimum detectable range. Given that the radar signal travels the speed of light, the transmitted pulse must shut off before the radar signal reaches and reflects from the target and returns to the receiver.

TARGET SPEED

The amount of frequency shift of the returned signal relative to the known frequency of the transmitted signal determines the relative speed of the target. What could cause the frequency of the radar return to differ from the transmitter frequency? The answer is Doppler shift. Everyone is familiar with the phenomenon even if not the term "Doppler shift." As a plane passes by as in Figure 3, it has a higher pitch tone as it approaches than it does after it passes by. This is Doppler shift. The sound waves are traveling at a fixed speed, but the waves are compressed as the car approaches, creating an increase in frequency. As the car passes by, the waves stretch, i.e., the peaks spread apart. This causes a decrease in the frequency or a lower pitch sound. The same phenomenon occurs with the electromagnetic waves of a radar signal. A stationary target will return a pulse of $A\cos(2\pi f_o t)$, where f_o is the radar transmitter frequency. An approaching target with a closing speed of v will return a pulse of

$$A\cos\left[2\pi f_o\left(1+\frac{v}{c}\right)t\right] = A\cos\left[2\pi\left(f_o+\frac{v}{\lambda_o}\right)t\right] \tag{9}$$

where λ_o is the wavelength from the stationary target. A retreating target will have a negative Doppler shift. If the target is not traveling straight toward the radar, but rather makes an angle as in Figure 3, the frequency will be

$$f = f_o + \frac{v}{\lambda_o}\cos\theta = f_o\left(1+\frac{v\cos\theta}{c}\right) \tag{10}$$

for closing targets, and

$$f = f_o - \frac{v}{\lambda_o}\cos\theta = f_o\left(1-\frac{v\cos\theta}{c}\right) \tag{11}$$

for retreating targets. By determining the difference between the transmitted frequency and the frequency of the received radar return, the radar system can determine the relative speed with respect to the radar.

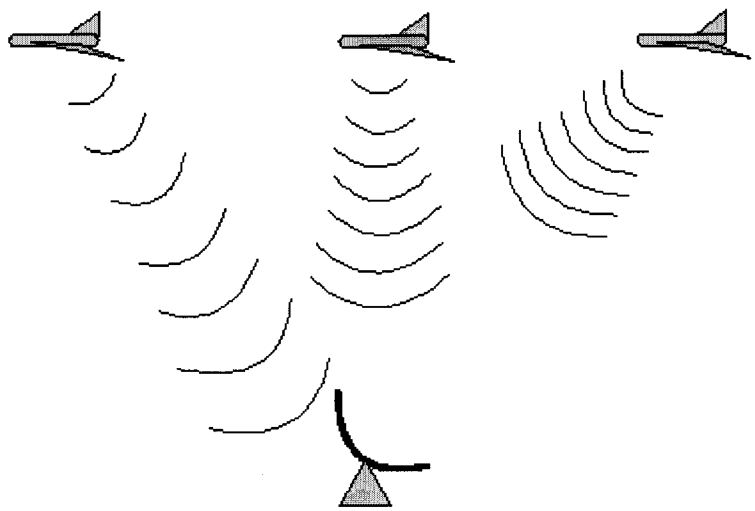

Figure 3 *Doppler shift from passing target.*

Example 3 Doppler Shift

Determine the frequency of a 2-GHz radar return for an aircraft approaching at 180 meters per second.

Given: $f_o = 2GHz$

$v = 180\frac{m}{s}$

Find: Doppler shifted frequency, f

Solution: $f = f_o\left(1+\frac{v\cos 0}{c}\right) = 2GHz\left(1+\frac{180\frac{m}{s}}{3\times10^8\frac{m}{s}}\right) = 2.0000012GHz$

Answer: $2GHz + 1.2kHz$

RADAR EQUATION

In EE 343 and EE 447 you will derive the Friis transmission equation for radio propagation in free space. We will now adapt that equation to radar. The amount of transmitted power from the radar that hits the target will be

$$P = P_T G_T \frac{RCS}{4\pi R^2} \tag{12}$$

where P_T and P_R are the power transmitted and received, respectively, G_T is the transmitter antenna gain, R is the distance from the radar to the target, and RCS is the area of the target in m^2 called "radar cross section" (RCS). The value of RCS accounts for the amount of Watts/m^2 of power density that is converted into Watts of power received by the target and is reflected from the target. Remember that the power radiated by the radar antenna decreases with the distance squared. Compare this to the power that is received at the radar by the reflection from the target. We can think of the power received in equation 12 as the power that is retransmitted or reflected by the target. The RCS takes into account any power received that is not reflected. Therefore, the power density radiated back toward the radar a distance R from the target is

$$S = \left(P_T G_T \frac{RCS}{4\pi R^2} \right) \left(\frac{1}{4\pi R^2} \right) = \frac{P_T G_T RCS}{(4\pi)^2 R^4} \tag{13}$$

The total power received by the radar antenna from the target reflection is this power density times the effective area of the receiving antenna, which in this case is the same antenna as the transmitting antenna. Therefore,

$$P_R = \left(\frac{P_T G_T RCS}{(4\pi)^2 R^4} \right) \left(G_T \frac{\lambda^2}{4\pi} \right) = \frac{P_T G^2 RCS}{(4\pi)^3 R^4} \tag{14}$$

where $A_{eff} = G\frac{\lambda^2}{4\pi}$ is the *effective area* of a receive antenna.

Note that the power received by the radar after making a round trip to the target and back decreases with the distance to the fourth power. Compare this to Friis transmission equation for one-way propagation.

So far we have referred to the received power rather than received energy. After all, the quality of the received signal in most receivers, including your car radio, is determined by the received power. However, most modern radar receivers have the ability to integrate their received power over the duration of the pulse width and extract all the energy in the pulse. Therefore, the longer the pulse duration, the more energy the receiver can detect giving a better signal-to-noise ratio. This creates two competing constraints. For radar sensitivity it is better to have as long of a pulse as possible. However, to determine range close to the radar, and to increase the ability for the radar to distinguish between closely spaced targets with slightly different ranges, it is better to have as short of a pulse as possible. Part of radar engineering is to determine the optimum parameters, including pulse width, for the operational needs of the radar system.

ELECTRONIC COUNTERMEASURES

As with most military operations, once radar was developed, electronic countermeasures (ECM) were almost immediately developed to counteract it. Some ECM are in the form of radar jamming, chaff, active decoys, and even defense suppression missiles such as the high speed anti-radiation missile (HARM). However, before these countermeasures can be deployed, it is necessary to detect and characterize the radar being defeated. It is certainly important for the pilot of a Wild Weasel mission to know whether the aircraft is being illuminated by a hostile surface-to-air missile (SAM) site or friendly weather radar. This is especially true if the intent is to launch a HARM missile that directs itself toward the radar emission for the purpose of destroying the radar installation (or at least its antenna).

A comparison of equation 14 with equation 12 suggests that the electronic warfare receiver used for ECM has an overwhelming advantage over the opposing radar. Remember the power receive after a one-way path from radar transmitter to ECM receiver decreases with the distance squared. Meanwhile the power received by the radar, after making a round trip to the target, decreases with the distance to the fourth power. Furthermore, not the entire transmitted signal that is intercepted by the target is reflected back to the radar. However there is more to this comparison than we have discussed so far.

All receivers are plagued by unwanted electronic noise, whether naturally occurring or generated by other electronic equipment. Electrical noise naturally occurs in all electronic devices and is directly proportional to the bandwidth of the device. This is where the radar receiver has the advantage over the ECM receiver. Since the radar generated the signal that it receives, its receiver can be carefully optimized for the exact characteristics of the signal it expects to receive, including the bandwidth. Therefore, the radar receiver's bandwidth is no larger than absolutely necessary to accurately receive the signal including a small amount of Doppler shift. In contrast, the ECM receiver must detect all types of radar signals at drastically different frequencies, without having perfect knowledge of the characteristics of the hostile radars. As a result, the ECM receiver's spectrum ranges from UHF to SHF or from around 1 GHz to above 18 GHz. This is an incredibly large bandwidth compared to that used by the radar receiver. Therefore, the ECM receiver has many times greater noise power than the radar receiver, which drastically decreases its sensitivity compared to the radar receiver. To counteract this disadvantage, the ECM receiver typically does not detect the entire 1-18GHz bandwidth simultaneously. Rather it dwells on a smaller bandwidth as it sweeps across the radar spectrum. However, this takes time. While the ECM receiver is dwelling on one part of the radar spectrum, it is blind to all other parts. One common technique that addresses this problem is to use channelized receivers. A channelized receiver consists of several parallel receivers that simultaneously receive different smaller bands of the larger radar bandwidth. Even so, the ECM receiver can never achieve the sensitivity level of the radar receiver without taking too long or being too large to be operationally useful. As you can see, each side has advantages and disadvantages that each tries to exploit from the other.

SUMMARY

Radar receives a reflected signal from a target based on the target's RCS. The transmitted signal may either originate from the radar system, in the case of monostatic radar, or it may be generated from an unrelated source, as the case of bistatic radar. From the radar return, the radar can determine range, direction, and speed of the target. In general, radars operate in two types of modes: surveillance or acquisition, and tracking. A radar system is an application of the concepts studied in most of your courses taken as an electrical-engineering major. This includes signals parameters, signal processing, analog and digital communications, antennas, and propagation to name a few.

APPENDIX

EE332
Analog filter design

EE 333
Convolution
Signal characterization
Fourier analysis

EE 343
Electromagnetic wave propagation
Reflection and scattering
Radar cross section (RCS)
Radar range equation
Antenna theory
Electromagnetic interference

EE 434
Real-time SONAR/ultrasound lab
4-channel phased array
Transmit beam-steered pulse
Receive sample signal
Time gain compensation
Demodulate
Quadrature to Magnitude
Scanconvert rectangular to polar
Doppler shift

EE 444
Antenna design
More wave propagation
Radar equation

EE 447
Fourier analysis and power spectral density
Pulse modulation
Matched filter
Correlation
Signal to noise ratio
Probability of error

EE448
Propagation channels
Bistatic radar model

This supplemental handout covers:

- Radar overview
- Block diagram
- Radar Equation
- Pulse repetition interval and frequency
- Minimum detectable signal
- Receiver sensitivity
- Maximum unambiguous range
- Range resolution
- Doppler frequency
- Radar cross section of targets

In addition, EE 343 will cover: 8 lessons

- Antenna parameters
- Radar wave propagation
- Antenna theory and parameters
- Phased array antennas

EE 333 will cover 10 lessons

- Convolution of signals with LTIFs
- Signal characterization
- Fourier analysis

EE 447 will cover: 14 lessons

- Fourier analysis and power spectral density
- Pulse modulation
- Receiver noise
- Matched filter
- Correlation
- Signal-to-noise ratio
- Probability density functions,
- detection and false alarm rate (Bit Error Rate, BER).

EE 434 will cover 7 lessons

- Real-time SONAR/ultrasound lab
- 4-channel phased array
- Transmit beam-steered pulse
- Receive sample signal
- Time gain compensation
- Demodulate
- Quadrature to Magnitude
- Scan convert rectangular to polar
- Doppler shift