Technical Report

Radar Principles

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Introduction

This paper will discuss many of the theoretical and physical principles that underlie the operation of radar systems. The word radar is derived from an acronym for radio detection and ranging. Radar is an electronic and electromagnetic system that uses radio waves to detect and locate objects. Radar operates by transmitting a particular kind of radio frequency waveform and detecting the nature of the reflected echo. When radio waves strike an object, some portion is reflected, and some of this reflected energy is returned to the radar set, where it is detected. The location and other information about these reflective objects, targets, can be determined by the reflected energy. Monostatic radars have transmitters and receivers that are co-located, whereas bistatic radars have transmitters and receivers that are physically separated. This paper will focus on monostatic radar, although many principles developed for monostatic radar can readily be transferred to bistatic radar.

Radio Wave Properties and Propagation

Radio waves have many properties including speed, frequency, and power; they display many phenomena such as refraction, attenuation, and reflection. The known speed and reradiation properties of radio waves are fundamental to the theory of radar operation, since radar systems are, at their core, transmitters and receivers of radio waves.

Electromagnetic waves are composed of both electric and magnetic fields, both of which oscillate perpendicular to each other and the direction of propagation. These transverse waves can be identified by certain characteristics, such as wavelength and frequency. Wavelength is the distance between successive peaks, whereas frequency is the number of peaks passing a point in a period of time. Radio waves occupy a portion of the electromagnetic spectrum from frequencies of a few kilohertz to a few gigahertz, less than one-billionth of the total electromagnetic spectrum.

In a vacuum, radio waves travel in straight lines. The speed of radio wave propagation in a vacuum (3×10^8 m/s) is a universal constant, c. The speed of wave propagation differs from c if the medium of propagation is matter. When electromagnetic waves travel in nonconducting materials, such as air, the wave speed v, is slower than c and is given by

$$v = \frac{1}{\sqrt{\varepsilon\mu}} \tag{1}$$

where ε and μ are the permittivity and permeability of the material, respectively. This velocity difference is not significant in air, but can have large effects for radars such as ground penetrating radar.

A measure derived from this wave speed change is the index of refraction, *n*, given by

$$n = \frac{c}{v_{\text{material}}} \tag{2}$$

A typical value of the index of refraction for air near the surface of the earth is 1.0003. A phenomenon called refraction occurs when radar waves pass through media with different indices of refraction. When a ray, the path of propagation of an electromagnetic wave, passes from a material having a smaller index of refraction to a material having a larger index of refraction, the ray is bent upwards. If the ray goes from a material having a larger index of refraction to a material with a smaller index of refraction, the ray is bent downwards.

The index of refraction of the atmosphere is not constant and depends on temperature, air pressure, and humidity. The temperature, partial pressure of the dry air, and the water vapor content normally decrease with increasing altitude; therefore, the index of refraction normally decreases with altitude. Since the velocity of propagation is inversely proportional to the index of refraction, radio waves move slightly more rapidly in the upper atmosphere than they do near the surface of the earth. The result is a downward bending of the rays towards the Earth. Since the rays are not straight, as in a vacuum, this effect can introduce error in elevation angle measurements.

A standard atmosphere is defined to have the index of refraction decrease uniformly at a rate of 4×10^{-8} per meter increase in altitude. In the presence of standard refraction, the curvature of the rays is less than the curvature of the earth. This extends the radar line of sight beyond the geometrical horizon. To simplify radar calculations, refracted rays are often replotted as straight-line propagation for a fictitious earth having a larger radius than the actual earth. For a standard atmosphere this effective radius is 4/3 the radius of the earth, though for nonstandard conditions the value may vary from 1.1 to more than 1.6 times the radius of the earth. The smaller values are more likely to exist in cold, dry climates or at high altitudes, whereas larger values occur in tropical climates. From trigonometry, one can determine the radar horizon range, the maximum distance that a radar can detect targets. The range is given by

$$r = \sqrt{2h_a kr_e} + \sqrt{2h_t kr_e} \tag{3}$$

where kr_e is the effective radius and h_a and h_t are the heights of the transmitter and target respectively.

Anomalous propagation, or ducting of electromagnetic waves occurs when the effective radius kr_e is greater than 2. This occurs when the gradient of the index of refraction of the atmosphere, *dn/dh*, is very large. If *dn/dh* is large enough, the radar rays could theoretically bend around the entire surface of the earth. The radar range is greatly extended with ducted propagation, but this results in a reduction of coverage in other directions. Regions with reduced coverage are called radar holes. These holes in coverage adversely affect airborne surveillance radar, as well as ground-based and ship-based systems.

Electromagnetic waves are traveling waves that transport energy from one region to another. The energy transfer can be described in terms of power transferred per unit area, for an area perpendicular to the direction of wave travel. In a vacuum, the energy flow per unit time per unit area, S, is given by

$$S = \frac{EB}{\mu_o} \tag{4}$$

where E and B are the electric and magnetic field magnitudes respectively, and μ_o is the permeability of free space. This can also be defined as the Poynting vector,

$$\vec{S} = \tfrac{1}{\mu_o} \vec{E} \times \vec{B} \tag{5}$$

The total power out of any closed surface is then

$$P = \oint \vec{S} \cdot d\vec{A} \tag{6}$$

The atmosphere can cause power to attenuate, depending on range and frequency. Attenuation peaks at certain frequencies due to absorption by atmospheric gases, such as water vapor at 22.24 GHz and oxygen at 60 GHz. Heavy rainfall also attenuates radar waves increasingly at higher frequencies.

Reflection at a definite angle from a very smooth surface is called specular reflection, whereas scattered reflection from a rough surface is called diffuse reflection. In radar applications, almost all reflection that is encountered is diffuse reflection. The transmitted waveform emitted from a radar is reflected by a target, and then detected by the radar to determine target location.

Doppler Effect and Moving Target Indication (MTI) Filtering

The frequency and wavelength of electromagnetic waves are affected by relative motion. This is known as the Doppler effect. Only the radial (approaching or receding) component of motion produces this phenomenon. If the source of an electromagnetic wave is approaching an observer, the frequency increases and the wavelength decreases. If the source is receding, the frequency decreases and the wavelength increases. An object's motion causes a wavelength shift $\Delta\lambda$, that depends on the speed and direction the object is moving. The amount of the shift depends on the source's speed, and is given by

$$\Delta\lambda = \frac{\lambda_{rest} v_{radial}}{c} \tag{7}$$

where c is the speed of light (or wave propagation speed if in material), λ_{rest} is the wavelength that would be measured if the source was at rest and v_{radial} is the speed of the source moving along the line of sight. The v_{radial} term only refers only to the component of velocity along the line of sight. If the target moves at an angle with respect to the line of sight, then the Doppler shift ($\Delta\lambda$) only informs about the part of motion along the line of sight. One must use other techniques to determine how much of an object's total velocity is perpendicular to the line of sight.

Radars use the Doppler effect to determine targets's velocity. Many radars use Doppler information only for determining target motion direction, whereas others determine speed of motion more precisely. Radars transmit radio waves of a set wavelength (or frequency), which then reflects off the target. In this case the target acts as a source, and its speed can be determined from the difference in the wavelength (or frequency) of the transmitted beam and reflected beam.

Unwanted radio wave reflections in radar systems are called clutter. Clutter can obscure desired targets. In classical military radar use, reflections from the ground, sea, weather, mountains, and birds, among other things are clutter. In weather radars, of course, reflections from storm systems are desired, and reflections from airplanes are clutter. Since clutter is unwanted, radars try to eliminate it using signal and data processing techniques. One of these techniques is based on the fact that targets of interest move, whereas most clutter does not. Using the Doppler effect's result that stationary objects will not have frequency shifts, the transmitted waveform frequency is filtered out of the received signal. As a result of this frequency domain filtering, only moving targets will remain. This process is called moving target indication filtering or MTI.

Radar Range Equation

The radar range equation relates the range of a radar system to the characteristics of its transmitter, receiver, antenna, target, and environment. In the simple form of the equation, propagation effects discussed earlier are ignored. If the power of the radar transmitter, P_t, is transmitted through an isotropic antenna, which radiates uniformly in all directions, the power density at a distance R from the radar will be

$$\text{power density} = \frac{P_t}{4\pi R^2} \tag{8}$$

Radars generally use directional antennas, which channel the transmitter power in a particular direction. The gain, G, of an antenna is the increased power in the direction of the target as compared to an isotropic antenna. When a directional antenna is used, the power density at distance R from the radar becomes

$$\text{power density of transmitted signal at target} = \frac{P_t G}{4\pi R^2} \tag{9}$$

Radar cross section (RCS), A_o, is a measure of the electromagnetic energy intercepted and reradiated at the same frequency by an object. To determine the RCS of an object, the reradiation properties are compared to an idealized object that is large, is perfectly conducting, and reradiates isotropically. An example of this is a large copper sphere, whose RCS is given by

$$\text{RCS of copper sphere} = \pi r^2 \tag{10}$$

where r is the radius of the sphere. When the transmitted pulse reaches the target, it is reradiated in all directions, so the power density of the echo signal at the radar is

$$\text{power density of echo at radar} = \frac{P_t G A_o}{4\pi R^2 4\pi R^2} \tag{11}$$

The radar antenna only captures a portion of the echo power. If the effective area of the radar antenna is denoted A_e, the power received by the radar, P_r, is

$$P_r = \frac{P_t G A_o A_e}{4\pi R^2 4\pi R^2} = \frac{P_t G A_o A_e}{(4\pi)^2 R^4} \tag{12}$$

The maximum radar range R_{max} beyond which the radar cannot detect targets occurs when the received echo signal is the minimum detectable signal, P_{min}. Hence,

$$R_{max} = \sqrt[4]{\frac{P_t G A_o A_e}{(4\pi)^2 S_{min}}} \tag{13}$$

As described previously, there is also a radar horizon range limitation, which may further limit the range of the radar. This simplified radar range equation is more of an upper bound, rather than a true measure of range limitation for practical radar systems.

Conclusion

The transmission and reception of radio waves is the fundamental operation of radar waves. Many properties and phenomena of radio waves are crucial to the operation of the radar system. The Earth's atmosphere plays a central role in radar operation, as it is the medium of propagation for the radio waveforms. The Doppler effect also plays a vital role in practical radar systems. Properties of the radar, the target, and the environment all contribute to determine the maximum range at which the radar can detect a target. Radar has numerous applications including air traffic control, meteorology, and military applications. Understanding the physical and theoretical underpinnings of radar systems is essential to understanding radar systems themselves.

List of Acronyms

MTI	Moving Target Indication
RCS	Radar Cross Section

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