

Radar Basics

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1. Introduction to Meteorological Radar

RADAR=**R**adio **D**etecting **A**nd **R**anging

Although the development of radar as a full-fledged technology did not occur until WWII, the basic principal of radar detection is almost as old as the subject of electromagnetism itself.

- Heinrich Hertz, in 1886, experimentally tested the theories of Maxwell and demonstrated that radio waves could be reflected by metallic and dielectric bodies (non-conductor of electricity).
- In 1903, a German engineer named Hulsmeyer experimented with the detection of radio waves reflected from ships and obtained a patent for an obstacle detector and ship navigational device. The German Navy showed no interest in the invention!
- In 1922, an excerpt from Marconi's lecture to the Institute of radio Engineers states: "It seems to me that it should be possible to design an apparatus by means of which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metal object, such as a steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby, immediately reveal the presence and bearing of the other ship in fog or thick weather".
- Marconi's suggestion motivated Taylor and Young of the Naval Research Laboratory to confirm experimentally the speculations by detecting a wooden ship. A proposal to develop this technology was refused!
- The first use of pulsed radar technique to measure distance was by Breit and Tuve, in 1925.
- The first radar detection of aircraft was in 1930 by L.A. Hyland of the Naval Research Laboratory (NRL). It was

made accidentally while he was working with a direction-finding, continuous wave apparatus installed on an aircraft on the ground.

- NRL started the development of pulse radar in 1934 through the efforts of R.M. Page, but he was not allowed to devote his full effort to the project!
- In 1935, NRL successfully tested pulsed radar with a range of 25-miles.
- Nineteen pulsed radars were installed on ships in 1941.

2. Development and Interpretation of the Radar Equation

Draw a Bi-Static Radar on the board with a spherical target.

Assume that a radar transmitter transmits a signal with power, P_t , into the atmosphere and that

Power Density from an Omni-directional Antenna in a non-absorbing atmosphere

$$\frac{P_t}{4\pi R^2} \quad \text{R is the Range to the Target}$$

Power Density from a Directional Antenna

$$\frac{P_t G_t}{4\pi R^2} \quad \text{G is the gain of the Transmit Antenna}$$

Power Reradiated in Radar Direction

$$\frac{P_t G_t \sigma}{4\pi R^2} \quad \text{Sigma is the *radar cross section*}$$

The power density of the echo is proportional to the power that is transmitted, the gain and aperture of the antenna (antenna characteristics) and inversely proportional to the range.

To establish the range from the radar to the target, most radar systems transmit pulses of specified duration into the atmosphere.

Show Slides:

- (1) range gates and resolution
- (2) signals and noise
- (3) signal averaging

If the radar wavelength is sufficiently larger than the target radius (Rayleigh Regime), the Radar Backscattering Cross-Section for a Spherical Target of Radius, a,:

$$\sigma_b = \frac{2^6 \pi^5 a^6}{\lambda^4} |K|^2$$

K is the dielectric constant of the target

The backscattering cross-section of a single droplet is proportional to the 6th power of the droplet radius and the inverse 4th power of the radar wavelength!

Define Reflectivity:

$$\eta(R) = \sum_{i=1}^N n_i \sigma_{bi} = \frac{2^6 \pi^5 |K|^2}{\lambda^4} \sum_{i=1}^N n_i a_i^6 = \frac{\pi^5 |K|^2}{\lambda^4} Z$$

where

$$Z = 2^6 \sum_{i=1}^N n_i a_i^6 \quad Z \text{ is generally reported as } \text{mm}^6/\text{m}^3$$

Measurements of intensity are often expressed in units of decibels (dB), which is a *relative*, logarithmic scale.

An example is the ratio between transmitted power, P_t , and received power, P_r , which is proportional to the target echo intensity, and the ratio of the received power, P_r , to the noise power in the receiver. The latter is known as the signal-to-noise ratio, SNR . The decibel scale is based on the log-10 power scale and a multiplier, and the two examples given above are written as

$$dB = 10 \log_{10} \left(\frac{P_t}{P_r} \right)$$

and

$$SNR(dB) = 10 \log_{10} \left(\frac{P_r}{P_n} \right)$$

Let's use the first of these equations to explore the meaning of decibels.

If $P_r = \frac{1}{10} P_t$, we produce a **-10 dB** change

What about a 50% reduction in received power?

If $P_r = \frac{1}{2}P_t$, we produce a -3 dB change

Because of the wide range in echo power intensity, the radar cross-section is often converted to decibels referenced to unity and known qualitatively as the more familiar dBZ units:

$$\text{dBZ} = 10 \log_{10} Z$$

Power Density of Echo Signal at Radar

$$P_r = \frac{P_t G_t A_r \eta}{(4\pi R^2)^2} \quad \text{A is the aperture of the Rx Antenna}$$

This equation is valid for an ideal radar system that is constantly transmitting energy and has no range resolution capability. The best way to determine the range to the target is to transmit a pulse of finite length and sample the power density at set times after the pulse has exited the antenna. We can establish the reflectivity characteristics of volumes at known distance from the radar using this technique.

After lengthy mathematical consideration of the impacts of a finite pulse length, taking logarithms, and recombining yields

$$\text{dBZ} = P_r(\text{dBm}) + 20 \log_{10} R + R_c$$

R_c is known as the radar constant and contains the impact of all radar hardware, including the transmit wavelength. The radar constant is system specific (unique for every radar).

Interpretation of the Radar Equation:

- 1) The power density received is a function of
 - 2) how much power is produced by the transmitter,
 - 3) the ability of the transmit antenna to focus this power in a given direction,
 - 4) the range to the target,
 - 5) the amount of the transmitted power that is absorbed by atmospheric gases (not discussed),
 - 6) the ratio between the inverse fourth power of the wavelength of the transmitted power and the sum of the individual return power densities of each droplet within the volume of atmosphere that is being illuminated. The return power of each droplet varies according to the 6th power of the droplet radius, and
 - a) the aperture (~gain) of the receive antenna.

- 7) The ability of the radar receiver to detect a return signal that can be discerned from the power density of thermal noise within the receiver electronics is determined by
 - a) the noise level,
 - b) the received power density, and
 - c) the number of pulses that we can average (not discussed).

- 8) The largest droplets in the illuminated volume tend to contribute disproportionately to the reflectivity. Suppose we have 1 droplet in a cubic meter that is 1000 microns (2 mm) radius and fifty that are 100 microns (0.1 mm) radius.

$$10 \log_{10} Z_{1000} = 10 \log_{10} [2^6 \times 1 \times 1^6] = 18.1 \quad \text{dBZ} \quad (1@1000 \text{ microns})$$

$$10 \log_{10} Z_{100} = 10 \log_{10} [2^6 \times 50 \times 0.1^6] = -24.9 \quad \text{dBZ} \quad (50@100 \text{ microns})$$

$$10 \log_{10} Z = 10 \log_{10} (2^6) + 10 \log_{10} (\{50 \times 0.1^6\} + \{1 \times 1^6\}) = 19.7 \quad \text{dBZ} \quad (\text{combined})$$

We see that the combined reflectivity is highly biased toward the reflectivity of the single large droplet despite the presence of a large population of smaller droplets in the same volume.

Interpretation of Radar Reflectivity

The Illusive Z-R Relationship

Radar literature is replete with all manner of expressions that attempt to relate radar reflectivity to the rainfall rate. The equations that attempt this magic are called Z-R relationships and they are often reported as power-law relationships of the following form:

$$Z = AR^p$$

In a typical Z-R relationship, A is a constant, R is the rainfall rate in arbitrary units, and p is a positive real number (decimal). There are dozens of Z-R relationships in the literature.

The flux of water (rainfall rate) through a horizontal plain (like the surface) depends upon the spectrum of droplet sizes because different droplet sizes have different fall velocities. The basic problem encountered when trying to relate radar reflectivity with the rainfall rate is that the radar reflectivity is proportional to the 6th power of the droplet radius, the water content of the droplets in the volume is proportional to the 3rd power of the droplet radius, and the fall velocity of raindrops drops is approximately inversely proportional to the 1st power droplet radius. If the fall velocity and liquid water content were to be proportional to the 6th power of the droplet size, as is the radar reflectivity, it would be possible to relate the radar reflectivity directly to the rainfall rate without specific knowledge of the spectrum of droplet sizes in the volume.

How do we beat the basic laws of physics? We measure the radar reflectivity above a point on the surface where the rainfall rate is being measured by a rain gauge and we plot the data on a graph. We fit these data to a power law relationship (of the form above) and use this relationship to map radar reflectivity into rainfall rates. How can such a technique be successful in light of the physical arguments given above? Well, it is because to first order, the rainfall rate is primarily a function of the largest droplets in the sample volume. The largest drops carry the bulk of the water and have the largest fall velocities, and therefore, contribute the most to the observed rainfall rate. Why are there so many different Z-R relationships? This is because the type and characteristic of precipitation varies widely from location to location on the planet, so local meteorologists often develop a “tuned” Z-R relationship for their region.

All hope is not lost, however, because the National Weather Service has recognized that Z-R relationships are futile, for the most part, and use rain gauges to “calibrate” the radars on an hourly basis. In other words, they use the radar data as a means to “upscale” calibrated data from a few spots.

There are also Z-R relationships for snow, but they are on much shakier fundamental footing than those for rain. The reason is that the radar backscattering cross section for snow is complex and difficult to determine. It varies widely from case to case (How many different configurations of snow have you seen?) and is temperature dependent.

The Radar Bright Band

- When snow melts into rain, the region where this melting occurs often has a stronger reflectivity than snow above or rain below; this region was hence given the name of "bright band".
- The bright band occurs just below the height of the 0°C level. Snow falls is composed of pure ice that is often falling in an oriented configuration, so its radar reflectivity is much lower than that of an "equivalent sphere" of liquid water.
- When snowflakes encounter the 0°C isotherm, they begin to melt. The surface of the snowflake becomes wet causing snow flakes to "clump" together into large aggregates. As the melting proceeds, a liquid spherical shell is formed around the remaining ice. Because ice is less dense than liquid, these "spongy wet spheres" have a larger size (radar cross section) than the same mass of pure liquid.
- As the ice at the core of the spongy wet droplet melts, the droplet "compresses" and accelerates toward the surface. Exceptionally large "clumps" of wet snowflakes evolve into rain drops that are too large to be dynamically stable. When this occurs, these large droplets divide into smaller droplets and their radar reflectivity is reduced.

Doppler Radar

Assume that a target is at a range, r , from a radar operative at a frequency, f_0 (corresponding to wavelength, λ). The total distance traversed by an impulse (narrow pulse) in going to the target and back to the antenna obviously is $2r$.

Measured in terms of wavelength, the distance is $2r/\lambda$ or, in radians

$$(2r/\lambda)2\pi = 4\pi r/\lambda \quad (\text{radians})$$

If the electromagnetic wave emitted by the antenna has a phase ϕ_0 , the phase after it returns will be

$$\phi = \phi_0 + \frac{4\pi r}{\lambda}$$

The change in phase as a function of time (from one pulse to the next) is

$$\frac{d\phi}{dt} = \frac{4\pi}{\lambda} \frac{dr}{dt}$$

If the target at range r is moving along the radar beam axis, the target velocity is

$$V = \frac{dr}{dt}$$

The angular frequency is:

$$\frac{d\phi}{dt} = \omega = 2\pi f$$

Making these two substitutions gives:

$$f = \frac{2V}{\lambda}$$

where f is the Doppler shift frequency and V is the radial velocity of the target, also called the “Doppler Velocity”.

It must always be remembered that the Doppler velocity measured by the radar is only a component of the actual wind - the part that is blowing towards or away from the radar. The

radar cannot measure the "crosswise" component. The actual wind will be at least as strong as the Doppler velocity, and possibly considerably stronger.

Hydrometeor Radars and Clear-Air Radars

Let's recall that "Heinrich Hertz, in 1886, experimentally tested theories of Maxwell and demonstrated that radio waves could be reflected by metallic and dielectric bodies (non-conductor of electricity)."

In free space electromagnetic waves propagate in straight lines because everywhere the dielectric permittivity and magnetic permeability are the same (constants related to the speed of propagation, actually).

The Earth's atmosphere has larger permittivity than free space and its permittivity is vertically stratified, so microwaves travel in curved paths at speeds less than the speed of light.

Sometimes their paths are so convoluted that they are bent back to the surface by this stratification. The path of a radar signal is determined by the change in height of the Earth's refractive index, n , which is a function of vertical gradients in temperature, pressure, and water vapor.

It can be shown that local variations in the refractive index give rise to the scattering of microwave signals!

The intensity of the scattering that is accomplished by these local gradients is a function of the strength of the temperature, pressure, or water vapor gradient and upon the strength of the turbulent eddies that are deforming it. Depending on the

intensity of the echoes from other targets in the scattering volume, the scattered energy from the refractive gradients generated by turbulent eddies of a given size (inertial subrange) may be detected by the radar receiver and the Doppler velocity measured.

Radar backscatter from turbulent eddies that have wavelengths that are one-half the transmitted wavelength can produce detectable signals at the antenna due to constructive interference (Bragg Scatter).

The refractive index structure parameter, C_n , which depends primarily on fluctuations in the moisture field, is used to quantify the scattering. The radar reflectivity that results from fluctuations in the moisture field is

$$Z_e = AC_n^2 \lambda^{11/3} \approx AC_n^2 \lambda^4$$

where

$$A = \frac{0.38}{\pi^5 |K_w|^2}$$

This equation that quantifies clear-air (not precipitating) echoes whose Doppler velocity can be measured. As the radar wavelength increases, the reflectivity of moisture fluctuations gets larger. Conversely, as the radar wavelength increases, the echoes from hydrometeors decrease at approximately the same rate, which is λ^4 !

About Marconi:

In 1895 Italian inventor Guglielmo Marconi built the equipment and transmitted electrical signals through the air from one end of his house to the other, and then from the house to the garden. These experiments were, in effect, the dawn of practical wireless telegraphy or radio.

Marconi built a transmitter, 100 times more powerful than any previous station, at Poldhu, on the southwest tip of England, and in November 1901 installed a receiving station at St. John's Newfoundland.