Level Measurement
Technology: Radar
Basic Principles of Radar

WHAT IS RADAR?

Radar, an acronym for the phrase radio detection and ranging, was applied to military use in the 1930s to detect the presence of aircraft. Today, radar has many useful applications. Examples of radar you are already familiar with include: the detection of storms to help pilots and weather forecasters avoid and predict bad weather, the use by law enforcement to measure the speed of an automobile, and the use of radar on small boats as a safety and navigation aid.

Radar is also similar to a familiar household device—the microwave oven. Radar devices and microwave ovens both produce electromagnetic waves. However, that is where the similarity stops. Whereas a microwave oven uses an electromagnetic wave to heat foods, radar typically uses an electromagnetic wave to determine distance and speed.

As it relates to level measurement, radar has been used for more than 50 years to measure the level of liquids in chemical transport tankers. Here radar is used to determine how much more cargo can be added without causing an overflow.

Since that time some form of radar has been used for precision level measurement in both the process and inventory industries: petroleum, power, chemical, food and beverage, pulp and paper, and pharmaceutical.

IS RADAR SAFE?

A radar device transmits an electromagnetic wave powered by a source of electrical energy. The entire arrangement of electromagnetic waves is called the electromagnetic spectrum (Figure 1).

The spectrum defines the frequency and wave length of different types of electromagnetic waves. Frequency refers to the number of vibrations or waves transmitted per second and is measured in Hertz, or cycles per second. Wave length is a measure of the length of each complete wave and is expressed in meters. Frequency and wave length are inversely proportional to each other; an electromagnetic wave with a high frequency has a short wavelength, and one with a low frequency has a long wavelength.

The most familiar frequency classification in the spectrum is light, the band of electromagnetic waves to which the eye is sensitive. Other common frequencies include TV and radio (FM and AM). An FM radio station transmits at 88 to 108 MHz (megaHertz). In comparison, radar gauges transmit in the frequency range between 3 and 30 GHz (gigaHertz).
Level Measurement

FIGURE 1. Electromagnetic Spectrum.

Most radar gauges today use the 5 to 10 GHz frequency range that was developed in military work over the past fifty years. Recent development has led to radar devices that use a frequency in the 24 GHz range. Use of the 24 GHz frequency allows the application of a much smaller antenna and beam width, which results in easier installation, compared to the larger and bulkier gauges that use the 5 to 10 GHz frequency.

If you examine the entire electromagnetic spectrum (Figure 1) you can see the highest frequencies—gamma rays, x-rays, and ultraviolet light—are the most harmful and well above the frequency used by radar. In other words, radar is just as safe as the constant radio, TV, cellular, and other communication waves that surround us everyday.

Another safety factor to consider is the amount of power used to transmit at a certain frequency. In this regard, a radar device is much safer than your microwave oven. The emitted signal of most radar level gauges is less than three percent of the maximum leakage allowed from this common household appliance.

TYPES OF RADAR SIGNALS

The two most common types of radar waves or signals used for level measurement are pulse radar and Frequency Modulated Continuous Wave, or FMCW for short.

Pulse Radar

Pulse radar gauges, frequently referred to as time-of-flight radar, transmit a short, noncontinuous pulse signal. The level of a product in a tank is based on the elapsed time it takes for the gauge to send a signal and receive the corresponding return signal (echo). Because all electromagnetic waves travel at the speed of light (approximately 186,000 miles per second), time must be measured in picoseconds (one trillionth of a second!). It is very difficult and expensive to build electronics that can measure time in picoseconds. This difficulty in measuring the time-of-flight precisely can cause accuracy errors.

In addition, pulse based radar systems have difficulty discriminating between multiple echoes and false return signals, from things such as agitators, blades, ladders and other obstructions within tanks.

FMCW Radar

Unlike pulse radar, FMCW radar gauges transmit a continuous signal that changes in frequency. When the signal reaches the surface of the material, the signal is reflected back to the radar gauge.

Instead of attempting to measure the time of flight, the receiver in the radar gauge evaluates the frequency difference between the transmitted signal and the return signal (Figure 2). Plotting these frequency differences against the transmitted signal yields a result that is proportional to the distance to, and thus level of, the material in the tank.

\[
\Delta t = \frac{\Delta f (\text{measured})}{m(\text{known})} d = \frac{c \Delta t}{2}
\]

FIGURE 2. FMCW Signaling.
**RADAR SIGNAL CHARACTERISTICS**

A basic principle of radar is its capability to reflect off the surface of materials based on the material’s dielectric constant. The dielectric constant of a material is directly proportional to the amount of electromagnetic energy that reflects from it. A vacuum has a dielectric constant of 1.0, which means it does not reflect a radar signal. Any material that has a dielectric constant greater than 1.8, such as water, crude oil, or ammonia, will easily reflect radar signals.

The higher the dielectric constant of the material, the more signal that is reflected and available for level measurement. On the other hand, radar signals tend to pass through materials that have a dielectric constant less than 1.8, such as air, vapor, certain gases, or foam. That is why radar is an excellent technology for measuring the level of a material in a tank; the air, vapor, or foam has minimal effect on level measurements, as compared with other level measurement technologies. In addition, changes in dielectric constants caused by changes in temperature or pressure have a minimal effect on the signal.

**RADAR LEVEL MEASUREMENT**

Radar gauges determine the level of a product in a tank by measuring the ullage (also called “outage”). The ullage, or vapor space, is the distance from the radar gauge mounting location to the surface of the material (Figure 3). The level measurement is determined by subtracting the ullage from the distance the radar gauge is mounted above the tank bottom (or reference gauge height.)

The reference gauge height is the fixed distance from the bottom of the tank (or strike plate) to the face of the radar gauge mounting flange. The reference gauge height establishes a reference point from which all level and calibration measurements are taken.

**BASIC RADAR GAUGE COMPONENTS**

At the top of a typical radar gauge, is the gauge housing (Figure 4). The gauge housing includes specially designed electronics for signal processing.

The radar electronics is the heart of the radar gauge. It produces an electromagnetic wave by using an oscillator that converts direct-current (dc) power into a microwave frequency or signal. It also receives the return signal.

The signal passes from the electronics through a waveguide. The waveguide is the entire path from the electronics to the antenna.

The antenna is typically a cone shaped device made of noncorrosive stainless steel. The antenna controls the signal beam width by helping to keep the signal focused on its target so it doesn’t spread out over the entire tank and give false echoes. The size of the antenna is inversely proportional to the frequency; the higher the frequency the smaller the antenna.
WHY FREQUENCY IS IMPORTANT
Radar gauges that operate in the 24 GHz frequency range provide significant advantages over lower frequency gauges. One advantage relates to beam width. The width of a radar beam is determined by using the formula:

\[
\text{beam angle} = \frac{70 \times \text{speed of light}}{\text{frequency} \times \text{antenna diameter}}
\]

To illustrate, assume the height of a tank, or Reference Gauge Height, is 20 feet (6.1 m).

![Figure 5. Frequency Beam Width Example.](LEVEL-0023A)

Using the previous formula yields the following results for 5, 10 and 24 GHz frequencies (Table 1).

<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>ANTENNA DIAMETER</th>
<th>BEAM WIDTH (at a distance of 20 ft.)</th>
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</thead>
<tbody>
<tr>
<td>A 5</td>
<td>4 in. (102 mm)</td>
<td>14.4 ft (6.1 m)</td>
</tr>
<tr>
<td>B 10</td>
<td>4 in. (102 mm)</td>
<td>9 ft (3.0 m)</td>
</tr>
<tr>
<td>C 24</td>
<td>4 in. (102 mm)</td>
<td>3.6 ft (1.2 m)</td>
</tr>
<tr>
<td>D 5</td>
<td>16 in. (483 mm)</td>
<td>3.6 ft (1.2 m)</td>
</tr>
<tr>
<td>E 10</td>
<td>10 in. (254 mm)</td>
<td>3.6 ft (1.2 m)</td>
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</table>

Table 1 shows that the lower frequencies (A, B) that use a 4-inch antenna transmit a wider beam; at 24 GHz (C), beam width is only four feet. To achieve an equal beam width, the lower frequencies require a much larger diameter antenna (D, E).

The narrower beam width helps to reduce unwanted signals from vessel obstructions such as agitators, heat exchangers, filling pipes, baffles, thermowells, intermittent filling streams, and other obstructions.

It allows greater flexibility in mounting the gauge on existing flanges located close to tank walls, without any problems.

Another advantage of the 24 GHz frequency relates to the use of a smaller, and thus lighter weight, antenna. A smaller and lighter weight unit makes it easier to transport and install on top of the tank. In addition, the antenna more easily accommodates existing small flanges.

RADAR GAUGE APPLICATIONS
Radar gauges are a noncontacting method of measuring level. The gauges provide an attractive alternative in processes where a standard insertion device becomes fouled or corroded.

The gauges are insensitive to many problematic liquid characteristics such as changing density, dielectric, or conductivity.

The advanced radar technology of the gauges provides accurate level measurement not found in other level technologies, while emitting safe signals in the microwave range. Its design is based on over 25 years of Rosemount® experience in process measurement instrumentation, coupled with the excellent service and support you have come to expect.

Now you have two radar gauges to choose from:

- The APEX™ Radar Gauge for tough, liquid level applications.
- The APEX Sentry™ Radar Gauge for less severe liquid level applications.
In most situations, both the APEX and APEX Sentry radar gauges effectively overcome the difficulties of level measurement problems, such as:

- agitation
- density changes
- vessel obstructions
- temperature changes
- vapors
- condensates
- changing dielectric

Because the APEX and APEX Sentry make use of advanced microprocessor based electronics they have no moving parts, which means they offer essentially trouble-free operation and reduced maintenance costs. In addition, HART\textsuperscript{®} protocol and a quick five-step, basic configuration make the APEX Radar Gauge exceptionally easy to use.

When selecting a level measurement technology, consider the reliability, accuracy, and versatility of radar technology; choose either the APEX or APEX Sentry Radar Gauge from Rosemount Inc.

### Basic Radar Principles Summary

- Radar is an acronym for Radio Detection And Ranging.
- Radar is just as safe as the radio, TV, and cellular communication waves that surround us everyday.
- The two most common types of radar signals are pulse radar and FMCW.
- Radar signals easily reflect from materials that have a dielectric constant greater than 1.8.
- Radar gauges determine the level of a product in a tank by measuring the ullage (distance to the product surface).
- The basic components of a radar gauge include: gauge housing, electronics, mounting flange, waveguide, and antenna.
- Radar gauges that operate in the 24 GHz frequency range are smaller and lighter weight than gauges operating at lower frequencies.
- A smaller beam width reduces unwanted signals from vessel obstructions.
- A smaller antenna and beam width provides easier installation and increased flexibility for mounting on existing flanges.
- Radar, in most situations, is impervious to conditions such as agitation, obstructions, vapors, temperature and density changes, condensates, and changing dielectric.
- Because there are no moving parts, radar gauges minimize maintenance costs.
### Glossary of Terms

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td><strong>antenna</strong></td>
<td>The cone-shaped metal part of a radar level gauge that directs the transmitted radar signal toward the surface of a material, and receives the corresponding return signal.</td>
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<tr>
<td><strong>dielectric</strong></td>
<td>A nonconductor of direct electric current; an insulator.</td>
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<td><strong>dielectric constant</strong></td>
<td>A measure of a material's ability to reflect microwave energy. Materials with a higher dielectric constant are more reflective of electromagnetic energy.</td>
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<tr>
<td><strong>electromagnetic spectrum</strong></td>
<td>The classification of electromagnetic waves by frequency and wave length.</td>
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<tr>
<td><strong>electromagnetic wave</strong></td>
<td>A wave in which both the electric and magnetic fields vary periodically, always at the same frequency.</td>
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<tr>
<td><strong>frequency</strong></td>
<td>The number of vibrations or waves transmitted per second. Frequency is measured in Hertz, or cycles per second.</td>
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<td><strong>FMCW radar</strong></td>
<td>Frequency Modulated Continuous Wave radar. A continuous radio signal that is generated with a changing (modulated) frequency to improve accuracy.</td>
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<tr>
<td><strong>gauge</strong></td>
<td>The entire radar device that includes the gauge housing, specially designed electronics, mounting flange, and antenna.</td>
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<tr>
<td><strong>Hertz</strong></td>
<td>A unit of frequency used to measure electromagnetic waves in cycles per second.</td>
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<tr>
<td><strong>microwave</strong></td>
<td>A comparatively short electromagnetic wave, between 1 mm and 1 meter in length. Microwaves are used by radar devices to detect the surface of a material.</td>
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<tr>
<td><strong>pulse radar</strong></td>
<td>A type of radar signal based on measuring the time-of-flight of a short, noncontinuous signal.</td>
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<tr>
<td><strong>radar</strong></td>
<td>An acronym for radio detection and ranging.</td>
</tr>
<tr>
<td><strong>radar electronics</strong></td>
<td>Produces an electromagnetic wave by using an oscillator that converts direct-current (dc) power into a microwave frequency or signal. It also receives the return signal.</td>
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<tr>
<td><strong>receiver</strong></td>
<td>The portion of the radar electronics that receives return signals reflected from the surface of a material.</td>
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<tr>
<td><strong>reference gauge height</strong></td>
<td>The fixed distance from the bottom of the tank (strike plate or other known data point) to the face of the radar gauge mounting flange.</td>
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<tr>
<td><strong>ullage</strong></td>
<td>Also called the outage. The amount that a tank lacks of being full. It can be thought of as the vapor space above the material in the tank.</td>
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<tr>
<td><strong>waveguide</strong></td>
<td>The entire path, from the electronics to the antenna, through which the radar signal travels.</td>
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