Selecting Radar Level Instruments for Custody Transfer

Which radar level technology is best for tank gauging in custody transfer applications, FMCW or Time of Flight?

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FIGURE 1. Radar level instruments have the necessary accuracy for custody transfer applications.

Measuring the level of tanks used to hold fluids for custody transfer can be expensive. This is not due to the cost of the measurement instrumentation, but to what inaccurate measurements can cost the company.

For example, consider a company with 10 oil tanks each filled and drained once a week. If the level instruments have ±3 mm accuracy per the company's technical specs, and each tank holds two million gallons, the uncertainty in the measurement is about 554 gallons per week. At $45 per barrel, that represents an error of $600. In one year of operation, that's $31,200 per year. Times 10 tanks, the error could potentially represent $312,000 per year in unnecessary losses due to less accurate Inventory Measurement.

Compare that loss to level instruments with 0.5 mm accuracy. The possible error is only 93.25 gallons per week, for a total cost of $52,000 per year. Installing better level instruments could save the company $260,000 per year in reporting unnecessary losses due to more accurate Inventory Measurement.

In many applications, higher-accuracy measurements are required to protect the customer from over-billing and the supplier from under-billing. Common products requiring this level of accuracy are typically oils, fuels, edible oils, and alcohols. In the oil & gas industry, this requires a system called automatic tank gauging (ATG) as defined by the American Petroleum Institute (API) standards.

For this same reason, groups around the globe either make recommendations or dictate the equipment accuracies needed when using level-based (static) inventory accounting for custody transfer, trading products or tax payment evaluation. Some of these groups, standards and guidelines are NMi, PTB, OIML R85 and API 3.1B. In general, these groups require a radar level instrument with better than 1mm level accuracy.

Frequency modulated continuous waveform (FMCW) and pulsed time-of-flight (ToF or PToF) are the two technologies used in modern radar-based tank gauging instruments, and there is often confusion about which is best. In reality they both perform to the specifications for custody transfer determined by the above groups. Both technologies have been around for well over 20 years and are proven in many applications, so the short answer is: Both technologies meet the stringent requirements for <1mm high-accuracy level measurement.

This article provides an overview of the differences between FMCW and ToF radars used for custody transfer.

Calculating Level

FMCW radar (Figure 2) transmits continuously, with the radar signal reflecting off the liquid surface received by the radar antenna. The shift in the frequency of the return signal is then used to calculate distance to the liquid. The calculations are:

1. $\Delta f \approx \Delta t$

Where running time t is a function of the change in frequency f

2. $d = t * c/2$

Where:
d = distance between instrument sensor and surface
t = running time
c = speed of light

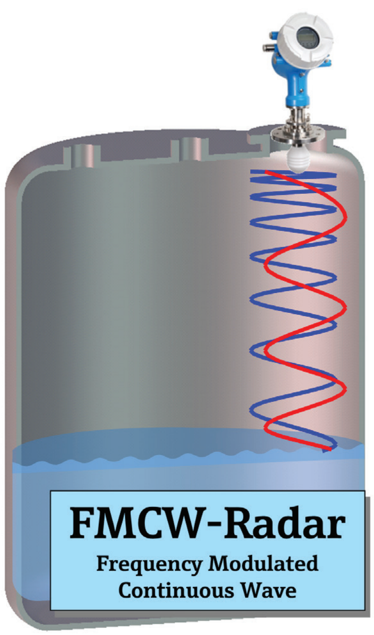


FIGURE 2. FMCW radar sends a continuous wave that reflects off the surface and returns to the antenna. The shift in frequency determines the level in the tank.

ToF radar (Figure 3) transmits energy in the form of a pulse which reflects off the liquid surface and is received by the antenna. The time it takes for this to happen is then used to calculate the distance to the liquid.

The level calculation is much simpler than FMCW as it is based on actual time:

$$d = t * c/2$$

Where:
d = distance between instrument sensor and surface
t = running time
c = speed of light

Refuting Sales Pitches

One of the problems in selecting the proper radar level instrument is dealing with sales pitches from suppliers.
A supplier selling one type of radar instrument but not the other might make various questionable claims which might have been true in the past, but are not any longer. Some of these sales pitches were:

- FMCW requires more power to operate than ToF, and needs a four-wire connection. This is no longer true. FMCW can be powered by a two-wire 4-20mA connection.
- FMCW is more expensive than ToF. No longer true. Pricing is now about the same
- FMCW is more accurate than ToF.. Both technologies meet the API Custody Transfer accuracy.
- FMCW has temperature stability problems. No longer true. In the past, FMCW radars used analog components requiring a stable temperature to produce a linear output. Today, digital components have solved the problem.

Essentially, there are no significant differences between the two technologies except for the algorithm used to calculate level. Selecting a radar level instrument, then, is more about the beam angle and the intended application.

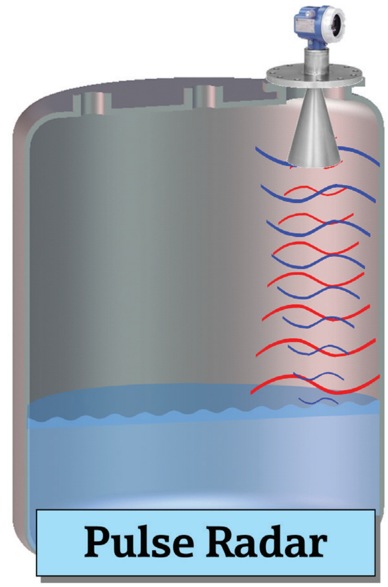


FIGURE 3. Pulse radar sends radar pulses that reflect off the liquid surface. The time of flight (ToF) determines the level of the liquid.

Frequency versus Beam Angle

As shown in Figure 4, the beam angle—the amount of spread in the radar signal—is dependent upon the size of the antenna and the frequency of the radar signal. For example, the largest spread of 23 degrees is produced by a low-frequency 6 GHz radar and a 6-inch antenna. The smallest spread of only 3 degrees is produced by a high-frequency 80GHz radar with a 4-inch antenna.

Beam angle is important because it determines how close the radar instrument can be installed to the tank wall (Figure 5). The beam should never reach the tank wall because it will interfere with the radar signal. For example, when a radar instrument with a large beam angle is installed too close to the side wall, this causes non-linear inaccuracies throughout the measurement range.

A narrow beam angle lets the instrument be installed close to the tank wall and makes it easier to find a location where it will not get a reflection off obstacles in the tank such as heating coils, fill/drain pipes or mixers.

Antenna Size	6 GHz	10 GHz	26 GHz	80 GHz
2”	---		18°	4°
3”	---		10°	3.5°
4”	---	21°	8°	3°
6”	23°	15°	5°	---
8”	19°	10°	4.4°	---
10”	15°	8°	3.3°	---
18”(17”)	7°	(6°)	---	---

FIGURE 4. Beam angles vary according to the frequency of the radar signal and the antenna size.

But a wide beam angle has its advantages. For example, a 6 GHz radar instrument has a lower, broader frequency than an 80 GHz instrument, so it’s better at penetrating steam and vapor. Wide beam angles are also beneficial in tanks with waves or agitation, as it provides more of an average representation of the liquid surface, and a 6GHz frequency is better when radar is used in stilling wells. For custody transfer storage tanks, the surface is calm so factors like steam, agitation, waves, etc. are not a factor.

Antenna size is important because it determines the size of the opening needed in the top of the tank. A drip-off lense antenna is preferred because condensed water or oil will drip off the antenna and not coat it.

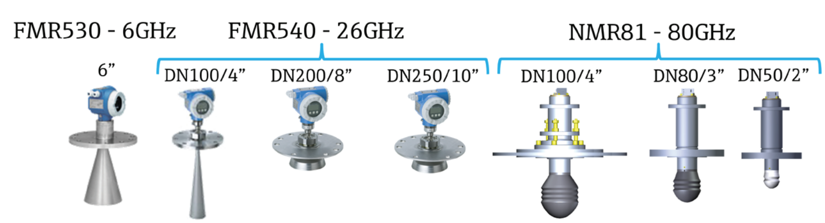
Ideally, a radar instrument should be installed as close to the tank wall as possible, given the limitations imposed by the beam angle and the size of the hole needed to mount it. Mounting it close to the tank wall minimizes the need for maintenance technicians to walk on the top of the tank when servicing the instrument, thus reducing safety hazards.

Also, the farther away from the sidewall of the tank, the less stable the radar’s gauge reference height (GRH) will be. Rain, ice, snow, temperature changes or someone walking on the roof to gauge the tank can easily cause several mm of deflection, which in turn changes the GRH of the instrument. Mounting the instrument close to the tank wall allows installation on the most rigid part of the roof, where the instrument is less affected by tank distortions.

For floating tank roofs, one solution is to mount the radar sensor inside a stilling well that’s not affected by the roof moving up and down. Some companies mount a lower accuracy radar 5-10 ft out from the side to measure a reflection off the roof itself, but that brings inaccuracies due to the roof tilting or water/snow accumulating and changing the buoyancy.

When selecting a radar level instrument, variables such as vessel height, the presence of obstructions, mounting distance from the side wall, available nozzle sizes, and other considerations may require testing by an instrument supplier and the end user to determine which solution is best for each application.
The most significant development in ATG applications is the 80GHz FMCW radar level instrument. Its narrow beam angle of three degrees is the smallest available, allowing it to be mounted closer to the tank wall than lower-frequency models. The antenna size of a 80GHz instrument is two to four inches in diameter, so it can be mounted in existing and smaller diameter nozzles, such as those used for older level instruments or locations where a company performs manual hand gauging .

FMCW technology has been around for many years, but it was cost-prohibitive in some applications until component and material costs came down. This is why 6-GHz or 26-GHz pulsed ToF radar was mostly used for level measurement.



Distance [m]	Distance to Wall [m]						
5	1,2	0,9	0,35	0,2	0,25	0,3	0,5
10	1,8	1,8	0,7	0,5	0,6	0,8	1,2
15	3	2,7	1,05	0,75	0,95	1,3	1,9
20	4	3,6	1,4	1,05	1,3	1,8	2,6
25	5	4,4	1,75	1,3	1,65	2,3	3,3
30	--	5,3	2,1	1,6	2	2,8	4

FIGURE 5. Distance the radar sensor can be mounted from the wall depends on the beam spread and height of the tank. For example, in a 15m (50 ft) tall tank, an 80GHz sensor with a 4-in. antenna can be mounted 0.95 m (3.11 ft) from the tank wall.

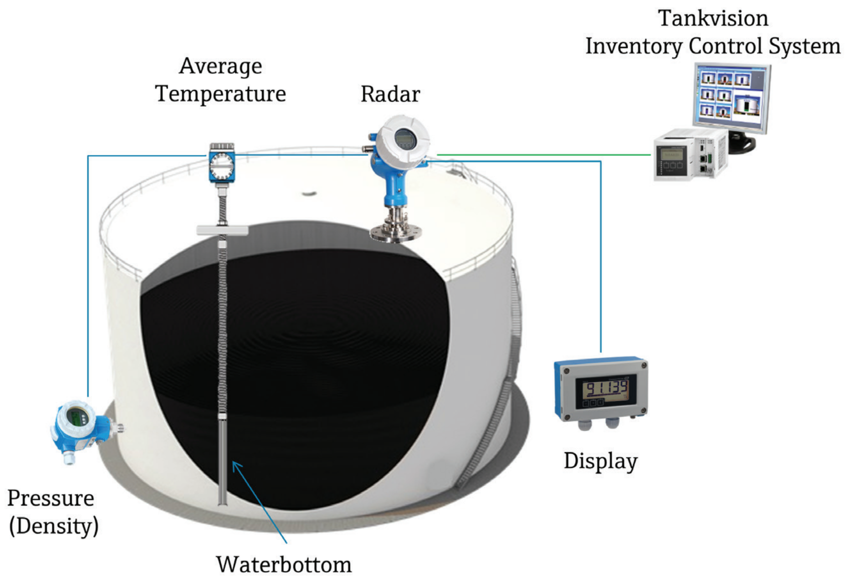


FIGURE 6. The waterbottom in a tank affects the level measurement of the oil floating above it. A complete tank gauging system needs level, temperature, waterbottom and pressure (when measuring mass) instruments, as well as inventory control software to process the data.

But converting from analog to digital components not only brought down the cost of FMCW instruments, it also allowed suppliers to add more capability to the instruments.

For example, Endress+Hauser's 80GHz device performs predictive measurements with its on-board microprocessor and alerts operators when problems arise. Diagnostic software checks electronics temperature, voltage inputs, near-field/by-horn measurements, and relative echo amplitude to determine the strength of a returning signal. These algorithms and diagnostics can be used to predict process upsets before they occur.

Beyond the Level

Most installations will include either a spot temperature or—for better inventory accountability—an average temperature based on up to 16 RTDs that measure temperature at various levels in the tank. The temperature is used to do volume correction based on the API tables.

Some applications require compensation for changes in density, when making a mass measurement. For these applications, a pressure instrument is included to provide the average mass measurement of the vessel contents.

In many vessels it is also necessary to measure water accumulated in the bottom of the vessel, called waterbottom (Figure 6). Most of the accumulation comes from water that drops out of petroleum- and oil-based liquids, but water can also come from vents in the vessel and gaskets on floating roof tanks. The water separates and sinks to the bottom of the vessel and must be accounted for to calculate the net standard volume (NSV) of product in a vessel.

One obvious reason for measuring the waterbottom is so only the desired product is measured and paid for in custody transfers, not the water. The measurement allows deduction of water from the NSV as part of the tank gauging system. Removing water is also done for maintenance reasons to prevent rust on the tank floor, which can lead to leaks and resulting environmental hazards. Waterbottoms are typically measured using a capacitance level instrument that can detect the interface between water and oil.

Calculating level, mass and volume from oil level, waterbottom level, pressure and temperature instruments in accordance with various regulations is usually accomplished by specialized tank inventory management software, which provides the corrected volume and/or mass using embedded API Tables.

Summary

Custody transfer and other critical tank gauging applications require a level instrument with extremely high accuracy. Both ToF and FMCW radar instruments provide the necessary accuracy to meet all regulations in the oil industry. The recent availability of 80GHz FMCW radar level instruments makes it possible to install level instruments closer to the tank wall for improved operations and stability, and also provides other benefits.

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