Radar level measurement
The user's guide

The user's guide

Peter Devine

Radar level measurement
- *The users guide*

Peter Devine

written by
Peter Devine
additional information
Karl Grießbaum
type setting and layout
Liz Moakes
final drawings and diagrams
Evi Brucker

Contents

4. Radar level measurement

The benefits of radar as a level measurement technique are clear.

Radar provides a non-contact sensor that is virtually unaffected by changes in process temperature, pressure or the gas and vapour composition within a vessel.

In addition, the measurement accuracy is unaffected by changes in density, conductivity and dielectric constant of the product being measured or by air movement above the product.

The practical use of microwave radar for tank gauging and process vessel level measurement introduces an interesting set of technical challenges that have to be mastered.

If we consider that the speed of light is approximately 300,000 kilometres per second. Then the time taken for a radar signal to travel one metre and back takes 6.7 nanoseconds or 0.000 000 006 7 seconds.

How is it possible to measure this transit time and produce accurate vessel contents information?

Currently there are two measurement techniques in common use for process vessel contents measurement. They are frequency modulated continuous wave (FM - CW) radar and PULSE radar

In this chapter we explain FM - CW and PULSE radar level measurement and compare the two techniques. We discuss accuracy and frequency considerations and explore the technical advances that have taken place in recent years and in particular two wire, loop powered transmitters.

FM-CW, frequency modulated continuous wave

The FM - CW radar measurement technique has been in use since the 1930's in military and civil aircraft radio altimeters. In the early 1970's this method was developed for marine use measuring levels of crude oil in supertankers. Subsequently, the same technique was used for custody transfer level measurement of large land based storage vessels. More recently, FM - CW transmitters have been adapted for process vessel applications.

FM - CW, or frequency modulated continuous wave, radar is an indirect method of distance measurement. The transmitted frequency is modulated between two known values, f_1 and f_2, and the difference between the transmitted signal and the return echo signal, f_d, is measured. This difference frequency is directly proportional to the transit time and hence the distance. (Examples of FM - CW radar level transmitters modulation frequencies are 8.5 to 9.9 GHz, 9.7 to 10.3 GHz and 24 to 26 GHz).

The theory of FM - CW radar is simple. However, there are many practical problems that need to be addressed in process level applications.

An FM - CW radar level transmitter requires a voltage controlled oscillator, VCO, to ramp the signal between the two transmitted frequencies, f_1 and f_2. It is critical that the frequency sweep is controlled and must be as linear as possible. A linear frequency modulation is achieved either by accurate frequency measurement circuitry with closed loop regulation of the output or by careful linearisation of the VCO output including temperature compensation.
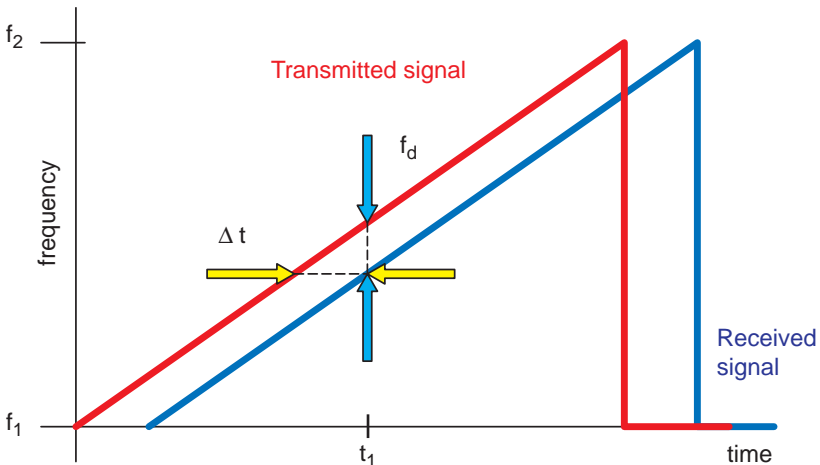
Fig 4.1 The FM - CW radar technique is an indirect method of level measurement.
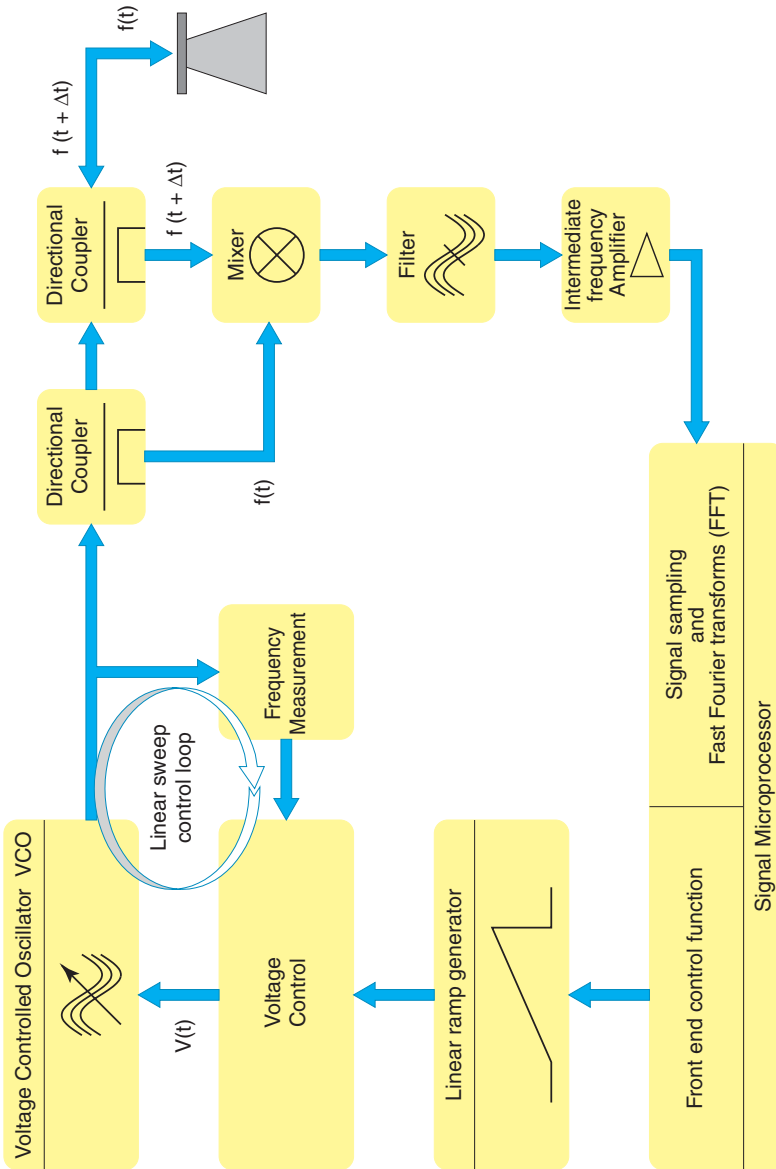*f_d is proportional to Δt which is proportional to distance*

Fig 4.2 Typical block diagram of FM - CW radar. A very accurate linear sweep is required

FM - CW block diagram (Fig 4.2)

The essential component of a frequency modulated continuous wave radar is the linear sweep control circuitry. A linear ramp generator feeds a voltage controller which in turn ramps up the frequency of the Voltage Controlled Oscillator. A very accurate linear sweep is required. The output frequency is measured as part of the closed loop control.

The frequency modulated signal is directed to the radar antenna and hence towards the product in the vessel. The received echo frequencies are mixed with a part of the transmission frequency signal. These difference frequencies are filtered and amplified before Fast Fourier Transform (FFT) analysis is carried out. The FFT analysis produces a frequency spectrum on which the echo processing and echo decisions are made.
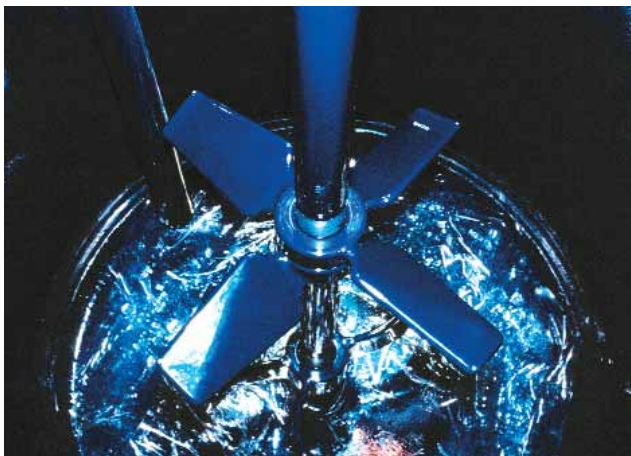
Pic 2 Typical glass lined agitated process vessel. A radar must be able to cope with various false echos from agitatior blades and baffles

Simple storage applications usually have a large surface area with very little agitation, no significant false echoes from the internal structure of the tank and relatively slow product movement. These are the ideal conditions for which FM - CW radar was originally developed.

However, in process vessels there is more going on and the problems become more challenging.

Low amplitude signals and false echoes are common in chemical reactors where there is agitation and low dielectric liquids.

Solids applications can be troublesome because of the internal structure of the silos and undulating product surfaces which creates multiple echoes.

An FM - CW radar level sensor transmits and receives signals simultaneously.

f_{d1}, $-f_{d2}$, $-f_{d3}$, $-f_{d4}$, $-f_{d5}$

Transmitted signal

Real echo signal

False echo signals
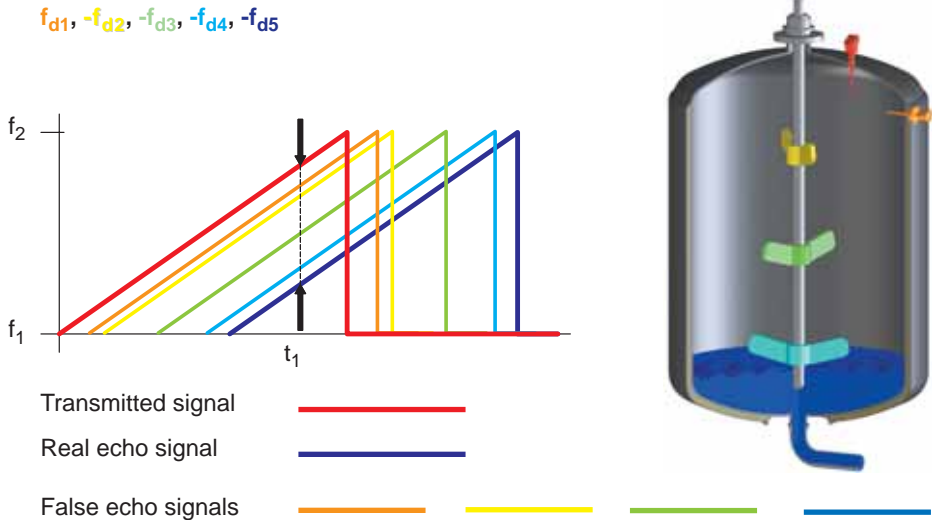
Fig 4.3a FM - CW radar level transmitters in an active process vessel

In an active process vessel, the various echoes are received as frequency differences compared with the frequency of the transmitting signal. These frequency difference signals are received by the antenna at the same time. The amplitude of the real echo signals are small compared with the transmitted signal. A false echo from the end of the antenna may have a significantly higher amplitude than the real level echo. The system needs to separate and identify these simultaneous signals before processing the echoes and making an echo decision.

The separation of the various received echo frequencies is achieved using Fast Fourier Transform (FFT) analysis. This is a mathematical proce-dure which converts the jumbled array of difference frequencies in the time domain into a frequency spectrum in the frequency domain.

The relative amplitude of each frequency component in the frequency spectrum is proportional to the size of the echo and the difference frequency itself is proportional to the distance from the transmitter.

The Fast Fourier Transform requires substantial processing power and is a relatively long procedure.

It is only when the FFT calculations are complete that echo analysis can be carried out and an echo decision can be made between the real level echo and a number of possible false echoes.

Mixture of frequencies received by FM - CW radar

f_{d1}, f_{d2}, f_{d3}, f_{d4}, f_{d5} etc combined
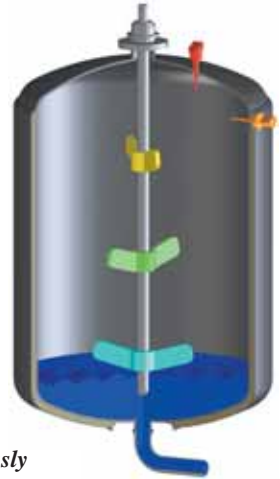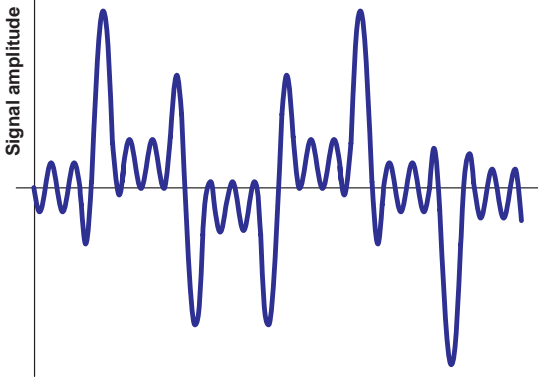
Fig 4.3b combined echo frequencies are received simultaneously

Combination of mixed difference frequencies received by FM - CW radar
Individual difference frequencies f_{d1}, f_{d2}, f_{d3}, are shown
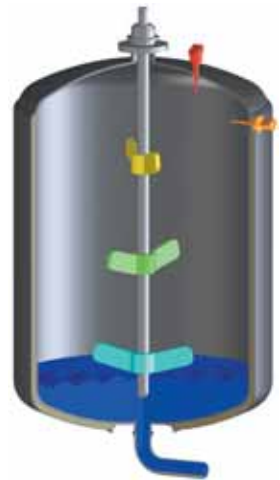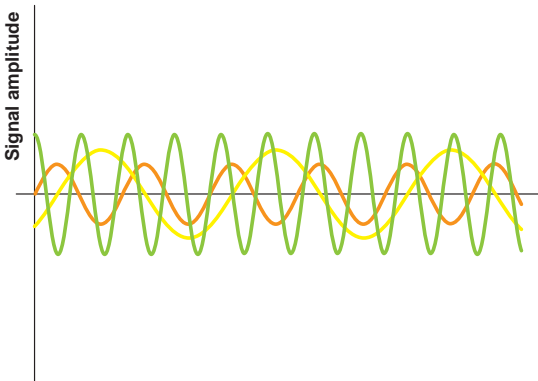
Fig 4.3c The individual frequencies must be separated from
the simultaneously received jumble of frequencies

Frequency spectrum echoes
Each echo is within an envelope curve of frequencies
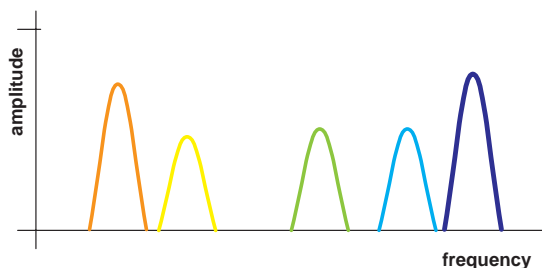
Fig 4.4 FM - CW frequency spectrum after Fast Fourier transform. The Fast Fourier transform algorithm converts the signals from the time domain into the frequency domain. The result is a frequency spectrum of the difference frequencies. The relative amplitude of each frequency component in the spectrum is proportional to the size of the echo and the difference frequency itself is proportional to the distance from the transmitter. The echoes are not single frequencies but a span of frequencies within an envelope curve
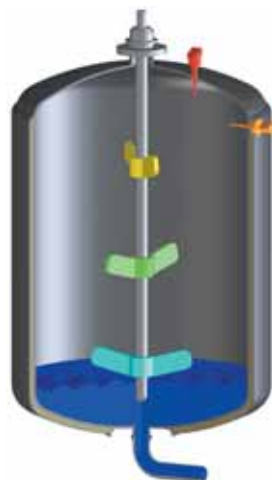
Complex process vessels and solids applications can prove too difficult for some FM - CW radar transmitters. Even a simple horizontal cylindrical tank can pose a serious problem. This is because a horizontal tank produces many large multiple echoes that are caused by the parabolic effect of the cylindrical tank roof. Sometimes the amplitudes of the multiple echoes are higher than the real echo. The processors that carry out the FFT analysis are swamped by different amplitude signals across the dynamic range all at the same time. As a result, the FM - CW radar cannot identify the correct echo.

As we shall see, this problem does not affect the alternative pulse radar technique.

PULSE radar level transmitters

Pulse radar level transmitters provide distance measurement based on the direct measurement of the running time of microwave pulses transmitted to and reflected from the surface of the product being measured.

Pulse radar operates in the time domain and therefore it does **not** require the Fast Fourier transform (FFT) analysis that characterizes FM - CW radar.

As already discussed, the running time for a distance of a few metres is measured in nanoseconds. For this reason, a special time transformation procedure is required to enable these short time periods to be measured accurately. The requirement is for a 'slow motion' picture of the transit time of the microwave pulses with an expanded time axis. By slow motion we mean milliseconds instead of nanoseconds.

Pulse radar has a regular and periodically repeating signal with a high pulse repetition frequency (PRF). Using a method of sequential sampling, the extremely fast and regular transit times can be readily transformed into an expanded time signal.
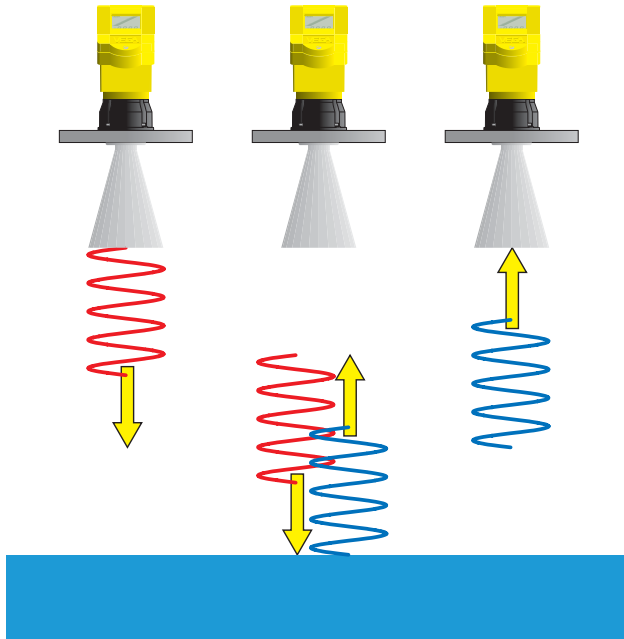
Fig 4.5 Pulse radar operates purely within the time domain. Millions of pulses are transmitted every second and a special sampling technique is used to produce a 'time expanded' output signal

To illustrate this principle, consider the sine wave signal in Fig 4.6. It is a regular repeating signal with a period of T1. If the amplitude (voltage value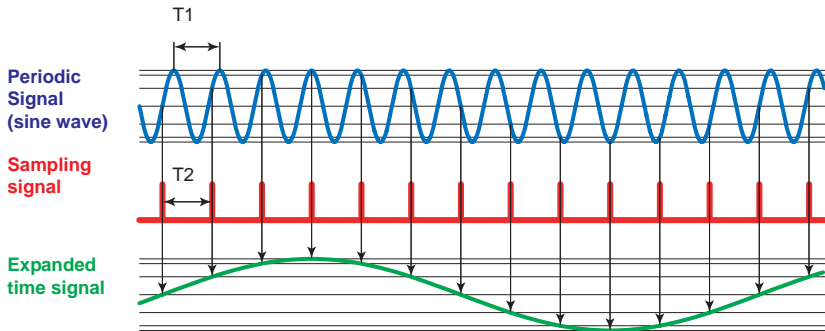) of the output of the sine wave is sampled into a memory at a time period T2 which is slightly longer than T1, then a time expanded version of the original sine wave is produced as an output. The time scale of the expanded output depends on the difference between the two time periods T1 and T2.

Fig 4.6 *The principle of sequential sampling with a sine wave as an example. The sampling period, T2, is very slightly longer than the signal period, T1. The output is a time expanded image of the original signal*

A common example of this principle is the use of a stroboscope to slow down the fast periodic movements of rotating or reciprocating machinery.

Fig 4.7 shows how the principle of sequential sampling is applied to pulse radar level measurement. The example shown is a VEGAPULS transmitter with a microwave frequency of 5.8 GHz.
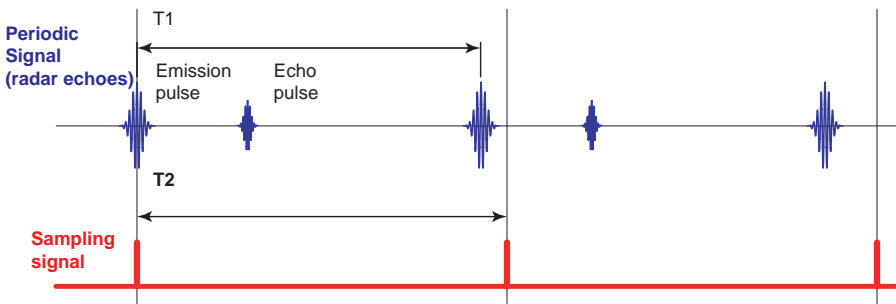
Fig 4.7 *Sequential sampling of a pulse radar echo curve. Millions of pulses per second produce a periodically repeating signal. A sampling signal with a slightly longer periodic time produces a time expanded image of the entire echo curve*

This periodically repeating signal consists of the regular emission pulse and one or more received echo pulses. These are the level surface and any false echoes or multiple echoes. The transmitted pulses and therefore the received pulses have a sine wave form depending upon the pulse duration. A 5.8 GHz pulse of 0.8 nanosecond duration is shown in Fig 4.8.

The period of the pulse repetition is shown as T1 in Fig 4.7. Period T1 is the same for the emission pulse repetition as for any echo pulse repetition as shown.

However, the sampling signal repeats at period of T2 which is slightly longer in duration than T1. This is the same time expansion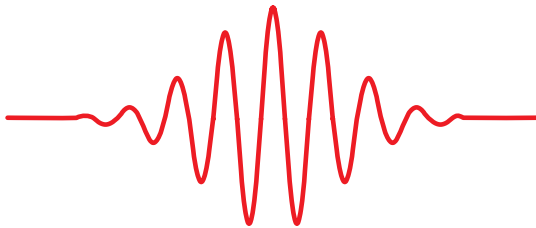 procedure by sequential sampling that has already been described for a sine wave. The factor of the time expansion is determined by T1 / (T2-T1).

Fig 4.8 Emission pulse (packet). The wave form of the 5.8 GHz pulse with a pulse duration of 0.8 nanoseconds

Example

The 5.8 GHz, VEGAPULS radar level transmitter has the following pulse repetition rates.

Transmit pulse 3.58 MHz	T1 = 279.32961 nanoseconds
Reference pulse 3.58 MHz - 43.7 Hz	T2 = 279.33302 nanoseconds

Therefore the time expansion factor is 81920 giving a time expanded pulse repetition period of 22.88 milliseconds.

There is a practical problem in sampling the emission / echo pulse signals of a short (0.8 nanosecond) pulse at 5.8 GHz. An electronic switch would need to open and close within a few picoseconds if a sufficiently short value of the 5.8 GHz sine wave is to be sampled. These would have to be very special and expensive components.

The solution is to combine sequential sampling with a 'cross correlation' procedure.

Instead of very rapid switch sampling, a sample signal of exactly the same profile is generated but with a slightly longer time period between the pulses.

Fig 4.9 compares sequential sampling by rapid switching with sequential sampling by cross correlation with a sample pulse.

Emission / Echo pulse

Sample signal

Sampling with picosecond switching

Sampling by cross correlation with a sample pulse
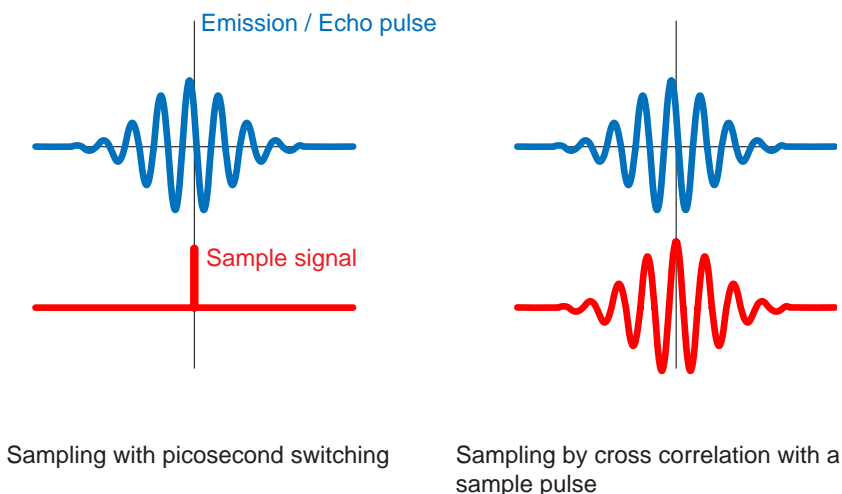
Fig 4.9 Comparison of switch sampling with 'cross correlation' sampling. The pulse radar uses cross correlation with a sample pulse. This means that rapid 'picosecond' switching is not required

Instead of taking a short voltage sample, cross correlation involves multiplying a point on the emission or echo signal by the corresponding point on the sample pulse. The multiplication leads to a point on the resultant signal. All of these multiplication results, one after the other, lead to the formation of the complete multiplication signal.

Fig 4.10 shows a short sequence of multiplications between the received signal (E) and the sampling pulse signal (M). The resultant E x M curves are shown on page 58.

Then the E x M curve is integrated and represented on the expanded curve as a dot. The sign and amplitude of the signal on the time expanded curve depends on the sum of the area of the E x M curve above and below the zero line. The final integrated value corresponds directly to the time position of the received pulse E relative to the sample pulse M.

The received signal E and sample signal M in Fig 4.10 are equivalent to the periodic signal (sine wave) and sample signal in Fig 4.6. The result of the integration of E x M in Fig 4.10 is directly analogous to the expanded time signal in Fig 4.6.
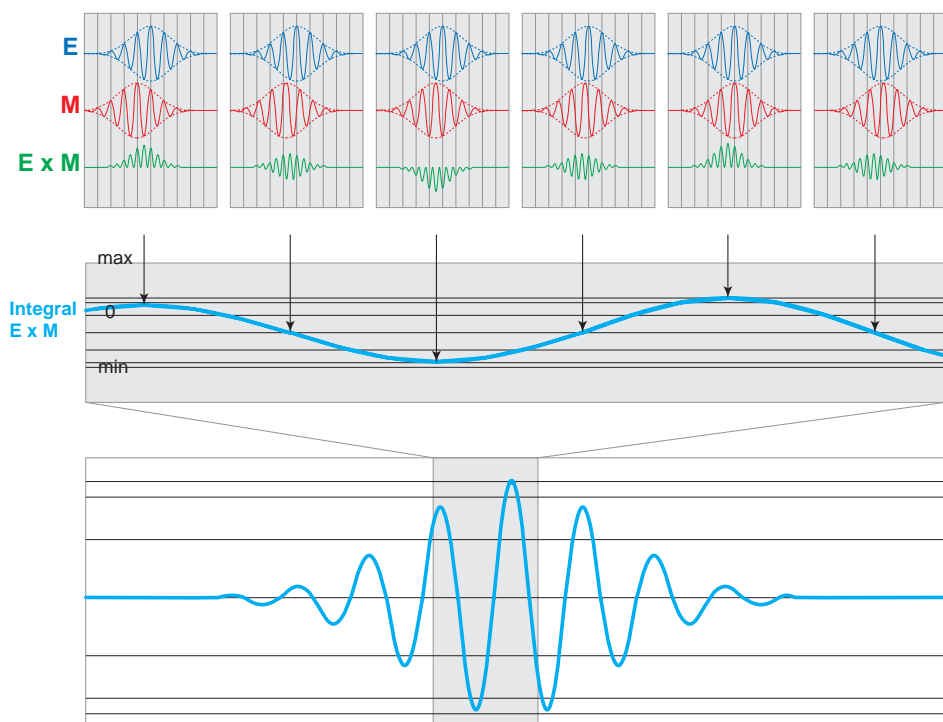
Fig 4.10 Cross correlation of the received signal E and the sampling *M*.
The product *E x M* is then integrated to produce the expanded time curve. The
technique builds a complete picture of the echo curve

The pulse radar sampling procedure is mathematically complicated but a technically simple transformation to achieve. Generating a reference signal with a slightly different periodic time, multiplying it by the echo signal and integration of the resultant product are all operations that can be handled easily within analogue circuits. Simple, but good quality components such as diode mixers for multiplication and capacitors for integration are used.

This method transforms the high frequency received signal into an accurate picture with a considerably expanded time axis. The raw value output from the microwave module is an intermediate frequency that is similar to an ultrasonic signal. For example the 5.8 GHz microwave pulse becomes an intermediate frequency of 70 kHz. The pulse repetition frequency (PRF) of 3.58 GHz becomes about 44 Hz.

Pulse echoes in a process vessel are separated in time
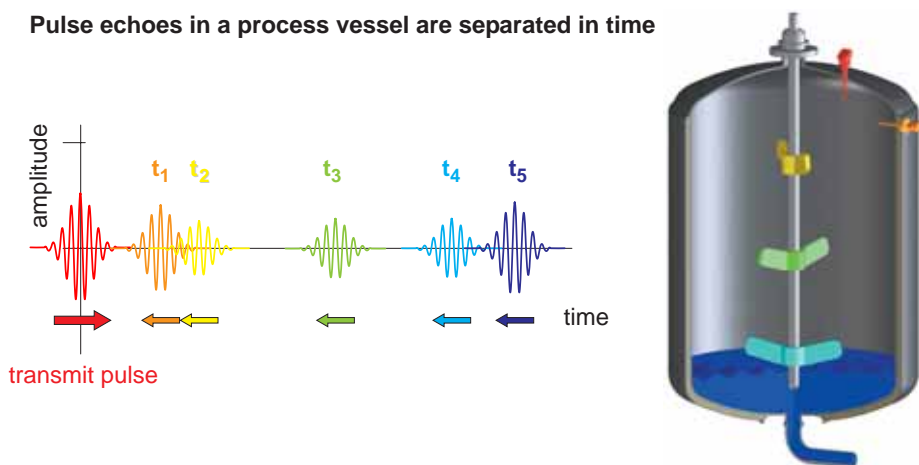
*Fig 4.12 **With a pulse radar, all echoes (real and false) are separated in time. This allows multiple echoes caused by reflections from a parabolic tank roof to be easily separated and analysed***

Pulse radar operates entirely within the time domain and does not need the fast and expensive processors that enable the FM - CW radar to function. There are no Fast Fourier Transform (FFT) algorithms to calculate. All of the pulse radar processing is dedicated to echo analysis only.

Part of the pulse radar transmission pulse is used as a reference pulse that provides automatic temperature compensation within the microwave module circuits.

The echoes derived from a pulse radar are discrete and separated in time. This means that pulse radar is better equipped to handle multiple echoes and false echoes that are common in process vessels and solids silos.

Pulse radar takes literally millions of 'shots' every second. The return echoes from the product surface are sampled using the method described above. This technique provides the pulse radar with excellent averaging which is particularly important in difficult applications where small amounts of energy are being received from low dielectric and agitated product surfaces.

The averaging of the pulse technique reduces the noise curve to allow smaller echoes to be detected. If the pulse radar is manufactured with well designed circuits containing good quality electronic components they can detect echoes over a wide dynamic range of about 80 dB. This can make the difference between reliable and unreliable measurement.

Frequency Conditioning

Microwave Module

Intermediate frequency

70.8 kHz
43.7 pulses / second

Intermediate Frequency Amplifier

Double diode Mixer

Low noise Amplifier

Microwave Pulse Generator
5,8 GHz

Microwave Pulse Generator
5,8 GHz

Reference pulse

directional Coupler

Antenna

Sampling pulses

Measurement pulses

Pulse Former

Mixer

Pulse Former

"Stand by"

Modulator

Frequency Measurement

Microprocessor Controller

3,58 mHz - 43,7 Hz

Frequency difference

3,58 mHz

Oscillator

Oscillator

Regulator

Tuner

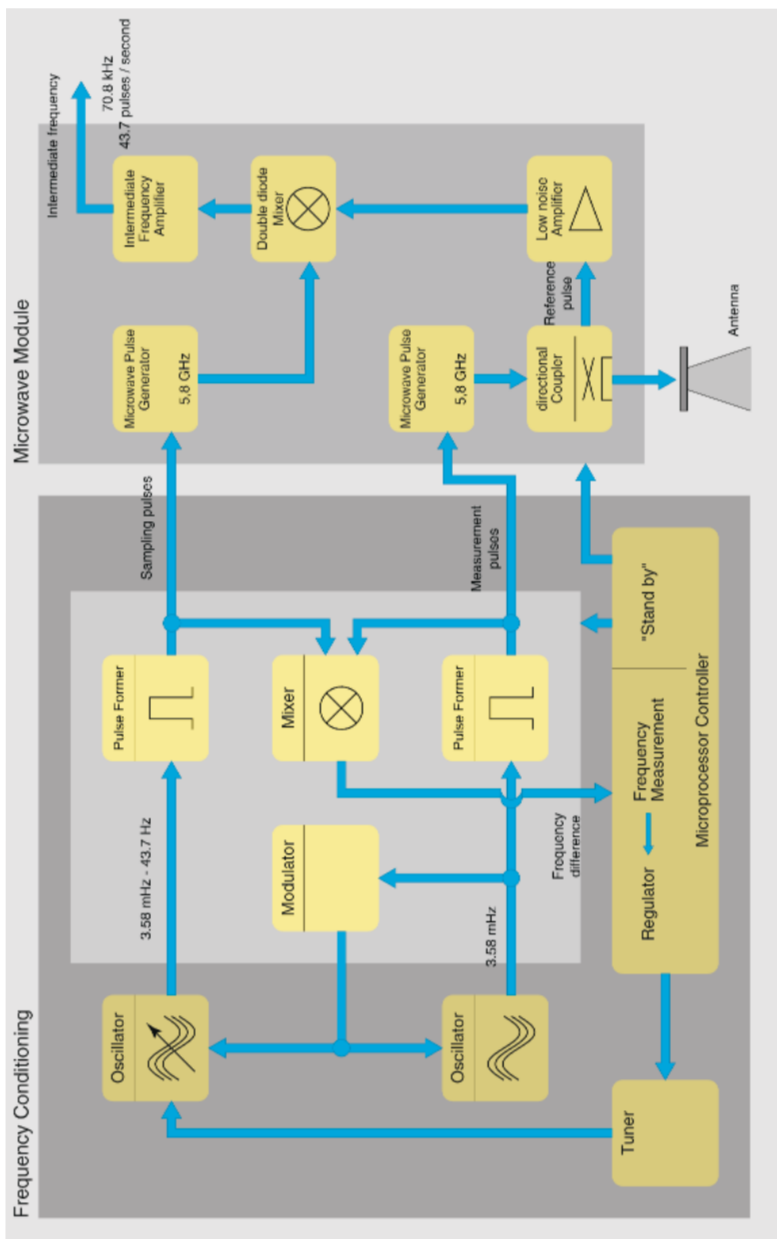*Fig 4.11 Block diagram of PULSE radar microwave module*

Pulse block diagram - (Fig 4.11)

The raw pulse output signal (intermediate frequency) from the pulse radar microwave module is similar, in frequency and repetition rate, to an ultrasonic signal.

This pulse radar signal is derived in hardware. Unlike FM - CW radar, PULSE does not use FFT analysis. Therefore, pulse radar does not need expensive and power consuming processors.

The pulse radar microwave module generates two sets of identical pulses with very slightly different periodic times. A fixed oscillator and pulse former generates pulses with a frequency of 3.58 MHz. A second variable oscillator and pulse former is tuned to a frequency of 3.58 MHz minus 43.7 Hz and hence a slightly longer periodic time. GaAs FET oscillators are used to produce the microwave carrier frequency of the two sets of pulses.

The first set of pulses are directed to the antenna and the product being measured. The second set of pulses are the sample pulses as discussed in the preceding text.

The echoes that return to the antenna are amplified and mixed with the sample pulses to produce the raw, time expanded, intermediate frequency.

Part of the measurement pulse signal is used as a reference pulse that provides automatic temperature compensation of the microwave module electronics.

Pic 3 Two wire pulse radar level transmitter mounted in a process reactor vessel

Choice of frequency

Process radar level transmitters operate at microwave frequencies between 5.8 GHz and about 26 GHz. Manufacturers have chosen frequencies for different reasons ranging from licensing considerations, availability of microwave components and perceived technical advantages.

There are arguments extolling the virtues of high frequency radar, low frequency radar and every frequency radar in between.

In reality, no single frequency is ideally suited for every radar level measurement application. If we compare 5.8 GHz radar with 26 GHz radar, we can see the relevant benefits of high frequency and low frequency radar.

2.6 GHz

5.8 GHz

Fig 4.14 Comparison of 5.8 GHz and 26 GHz radar antenna sizes. These instruments have almost identical beam angles. However this is not the full picture when it comes to choosing radar frequencies

Antenna size - beam angle

The higher the frequency of a radar level transmitter, the more focused the beam angle for the equivalent size antenna.

With horn antennas, this allows smaller nozzles to be used with a more focused beam angle.

For example, a 1½" (40 mm) horn antenna radar at 26 GHz has approximately the same beam angle as a 6" (150 mm) horn antenna at 5.8 GHz.

However, this is not the complete picture. Antenna gain is dependent on the square of the diameter of the antenna as well as being inversely proportional to the square of the wavelength.

Antenna gain is proportional to:-

$$\frac{diameter^2}{wavelength^2}$$

Antenna gain also depends on the aperture efficiency of the antenna. Therefore the beam angle of a small antenna at a high frequency is not necessarily as efficient as the equivalent beam angle of a larger, lower frequency radar. A 4" horn antenna radar at 6 GHz gives excellent beam focusing.

A full explanation of antenna gain and beam angles at different frequencies is given in Chapter 5 on radar antennas.

Focusing at different frequencies
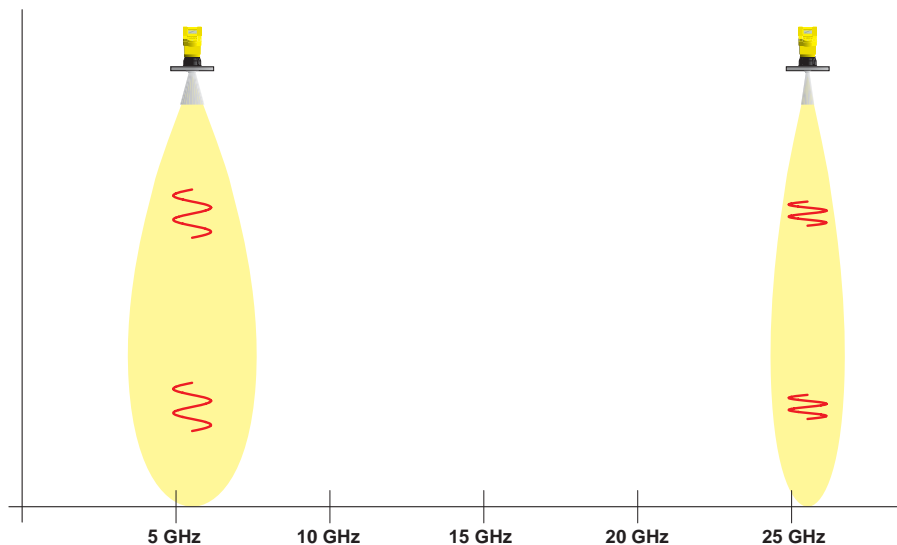
Fig 4.13 For a given size of antenna, a higher frequency gives a more focused beam

Antenna focusing and false echoes

A 26 GHz beam angle is more focused but, in some ways, it has to be.

The wavelength of a 26 GHz radar is only 1.15 centimetres compared with a wavelength of 5.2 centimetres for a 5.8 GHz radar.

The short wavelength of the 26 GHz radar means that it will reflect off many small objects that may be effectively ignored by the 5.8 GHz radar. Without the focusing of the beam, the high frequency radar would have to cope with more false echoes than an equivalent lower frequency radar.
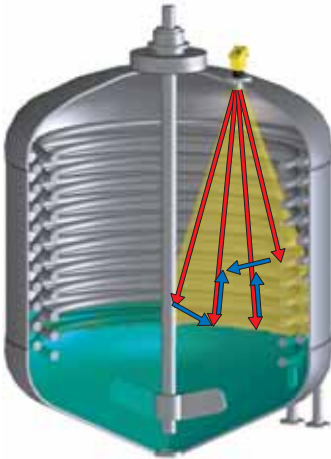
Fig 4.15 a Low frequency radar has a wider beam angle and therefore, if the installation is not optimum, it will see more false echoes. Low frequencies such as 5.8 GHz or 6.3 GHz tend to be more forgiving when it come to false echoes from the internal structure of a vessel or silo
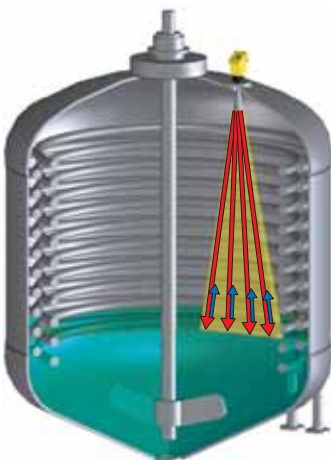
Fig 4.15 b High frequency radar has a much narrower beam angle for a given antenna size. The narrower beam angle is important because the short wavelength of the higher frequencies, such as 26 GHz, reflect more readily from the internal structures such as welds, baffles, and agitators. The sharper focusing avoids this problem
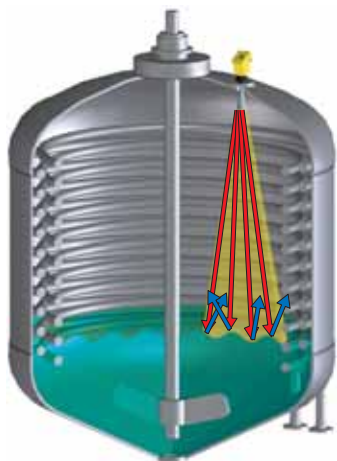
Agitated liquids and solid measurement

High frequency radar transmitters are susceptible to signal scatter from agitated surfaces. This is due to the signal wavelength in comparison to the size of the surface disturbance.

The high frequency radar will receive considerably less signal than an equivalent 5.8 GHz radar when the liquid surface is agitated. The lower frequency transmitters are less affected by agitated surfaces.

It is important that, whatever the frequency, the radar electronics and echo processing software can cope with very small amplitude echo signals. As discussed, pulse radar has an advantage in this area no matter what the frequency.

Fig 4.16 **High frequency radar transmitters are susceptible to signal scatter from agitated surfaces. This is due to the signal wavelength in comparison to the size of the surface disturbance. It is important that radar electronics and echo processing software can cope with very small amplitude echo signals. By comparison, 5.8 GHz radar is not as adversely affected by agitated liquid surfaces. Lower frequency radar is generally better suited to solid level applications**

Condensation and build up

High frequency radar level transmitters are more susceptible to condensation and product build up on the antenna. There is more signal attenuation at the higher frequencies, such as 26 GHz. Also, the same level of coating or condensation on a smaller antenna naturally has a greater effect on the performance.

A 6" horn antenna with 5.8 GHz frequency is virtually unaffected by condensation. Also, it is more forgiving of product build up.

Steam and dust

Lower frequencies such as 5.8 GHz and 6.3 GHz are not adversely affected by high levels of dust or steam. These frequencies have been very successful in applications ranging from cement, flyash and blast furnace levels to steam boiler level measurement.

In steamy and dusty environments, higher frequency radar will suffer from increased signal attenuation.

Foam

The effect of foam on radar signals is a grey area. It depends a great deal on the type of foam including the foam density, dielectric constant and conductivity. However, low frequencies such as 5.8 GHz and 6.3 GHz cope with low density foam better than higher frequencies such as 26 GHz.

For example, a 26 GHz radar signal will be totally attenuated by a very thin detergent foam on a water surface. A 5.8 GHz radar signal will see through this type of foam and continue to see the liquid surface as the foam thickness increases to 150 mm or even 250 mm.
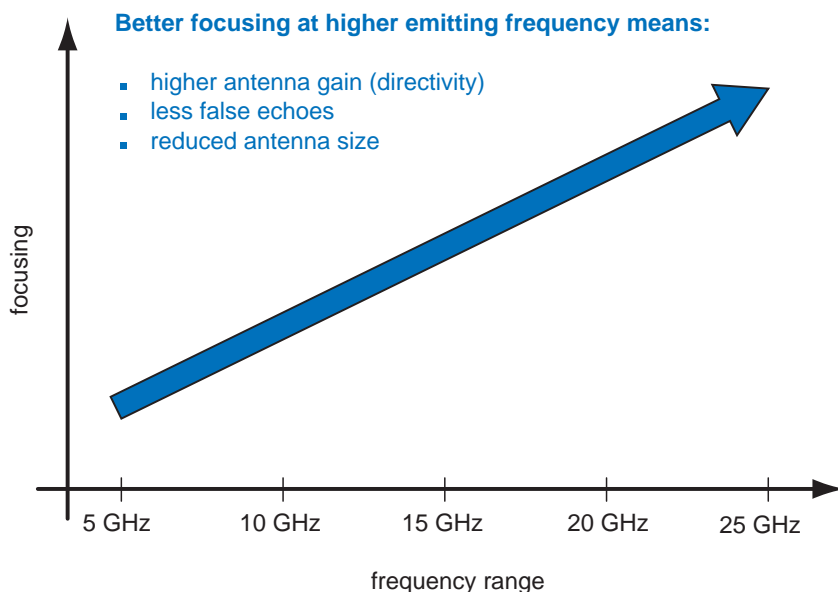
However, the thickness of foam will cause a small measurement error because the microwaves slow down slightly as they pass through the foam.

When foam is present, it is important to provide the radar manufacturer with as much information as possible on the application.

Minimum distance

Higher frequency radar sensors have a reduced minimum distance when compared with the lower frequencies. This can be an additional benefit when measuring in small vessels and stilling tubes.

Summary of the effects of radar frequency

Better focusing at higher emitting frequency means:

- higher antenna gain (directivity)
- less false echoes
- reduced antenna size

Fig 4.17 Focusing and radar frequency

Reduced signal strength caused by damping at higher emitting frequency caused by:

- condensation
- build - up
- steam and dust
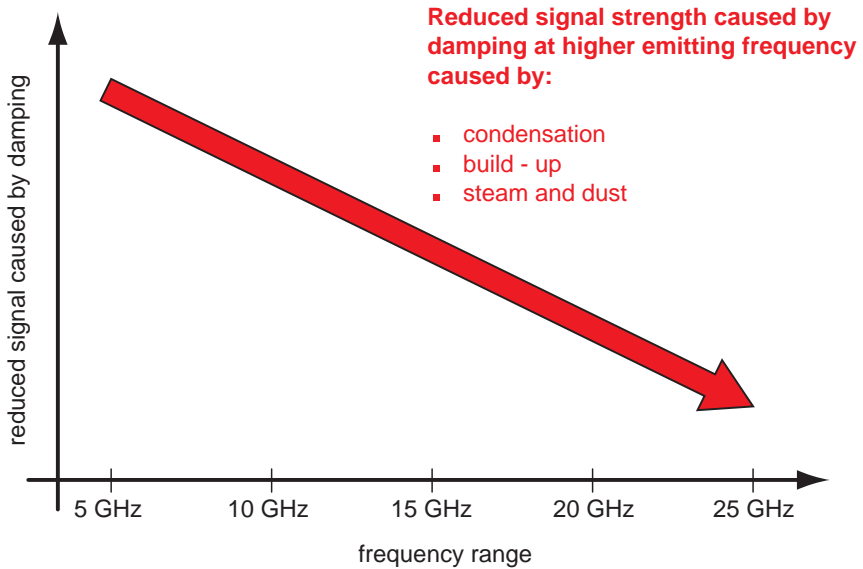
Fig 4.18 Signal damping and radar frequency

Higher damping caused by agitated product surface

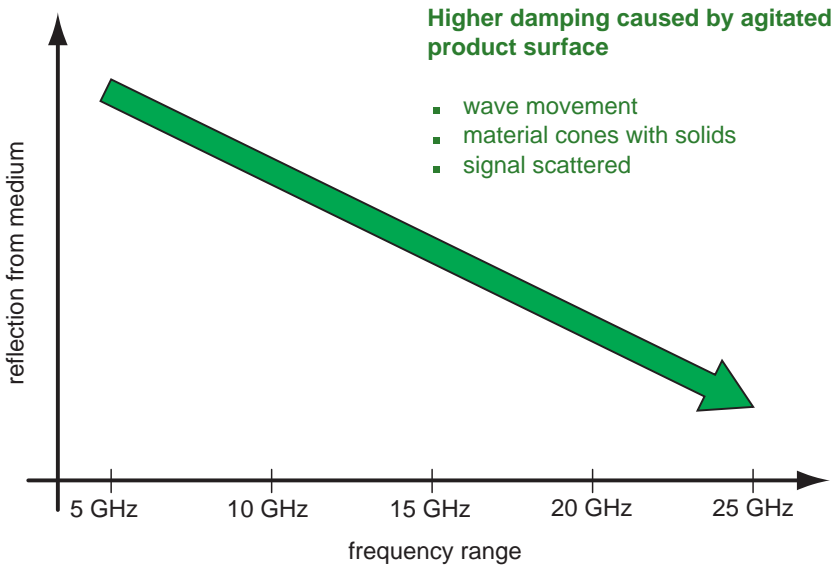- wave movement
- material cones with solids
- signal scattered

Fig 4.19 Signal strength from agitated and undulating surfaces and radar frequency

Accuracy

There is no inherent difference in accuracy between the FM - CW and PULSE radar level measurement techniques.

In this book, we are concerned specifically with process level measurement where 'process accurate' and cost effective solutions are required.

The achievable accuracy of a process radar depends heavily on the type of application, the antenna design, the quality of the electronics and echo processing software employed.

The niche market for custody transfer level measurement applications is outside the scope of this book. These custody transfer radar 'systems' are used in bulk petrochemical storage tanks. Large parabolic or planar array antennas are used to create a finely focused signal. A lot of processing power and on site calibration time is used to achieve the high accuracy. Temperature and pressure compensation are also used.

Range resolution and bandwidth

In process level applications, both FM - CW and PULSE radar work with an 'envelope curve'. The length of this envelope curve depends on the bandwidth of the radar transmitter. A wider bandwidth leads to a shorter envelope curve and therefore improved range resolution. Range resolution is one of a number of factors that influence the accuracy of process radar level transmitters.

Pulse radar bandwidth

The carrier frequency of a pulse radar varies from 5.8 GHz to about 26 GHz.

The pulse duration is important when it comes to resolving two adjacent echoes. For example, a one nanosecond pulse has a length of about 300 mm. Therefore, it would be difficult for the radar to distinguish between two echoes that are less than 300 mm apart. Clearly a shorter pulse duration provides better range resolution.

An effect of a shorter pulse duration is a wider bandwidth or spectrum of frequencies.

For example, if the carrier frequency of a pulse is 5.8 GHz and the duration is only 1 nanosecond, then there is a spectrum of frequencies above and below the nominal carrier frequency. The amplitude of the pulse spectrum of frequencies changes according to a

$$\frac{\sin x}{x}$$

curve.
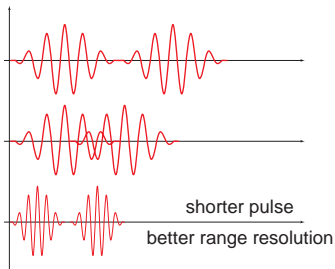
The shape of this curve is shown in Fig 4.21.

The null to null bandwidth BW_{nn} of a pulse radar is equal to
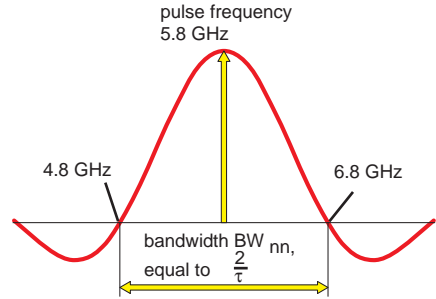
$$\frac{2}{\tau}$$

where τ is the pulse duration.

It is clear from the curve that the amplitude of frequencies reduces significantly away from the main pulse frequency.

Fig 4.20 *Pulse radar range resolution. The guaranteed range resolution is the length of the pulse. A shorter pulse has a wider bandwidth and better range resolution*


Fig 4.21 *The null to null bandwidth BW_{nn} of a radar pulse is equal to $2/\tau$ where τ is the pulse duration. Example a 5.8 GHz radar with a pulse duration of one nanosecond has a null to null bandwidth of 2 GHz*
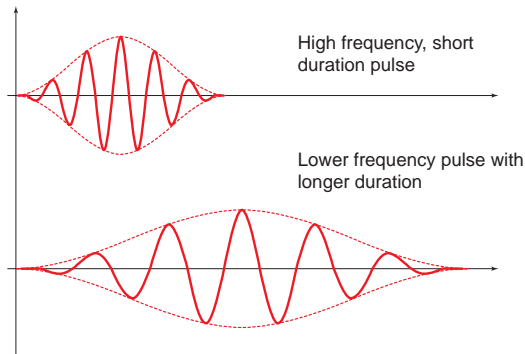
Pulse radar envelope curve

Fig 4.22 shows how a pulse radar echo curve is used in process level measurement.

A higher frequency pulse with a shorter pulse duration will allow better range resolution and also better accuracy because the leading edge of the envelope curve is steeper.
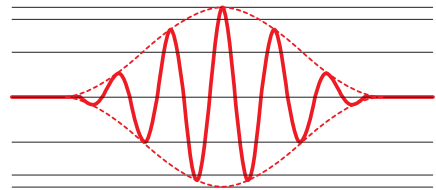
Fig 4.22 *Envelope curve with pulse radar*

Fig 4.23 *A shorter pulse duration gives better range resolution. The combination of shorter pulse duaration and higher frequency allows better accuracy because the leading edge of the envelope curve is steeper*

FM-CW radar bandwidth

The bandwidth of an FM - CW radar is the difference between the start and finish frequency of the linear frequency modulation sweep.

Unlike pulse radar, the amplitude of the FM - CW signal is constant across the range of frequencies.

A wider bandwidth produces narrower difference frequency ranges for each echo on the frequency spectrum. This leads to better range resolution in the same way as with shorter duration pulses with pulse radar.
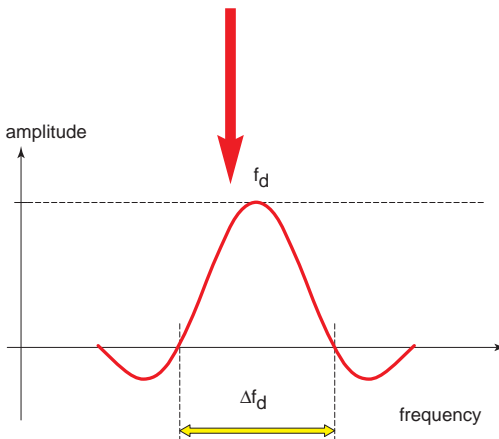
This is explained in the following diagrams and equations.
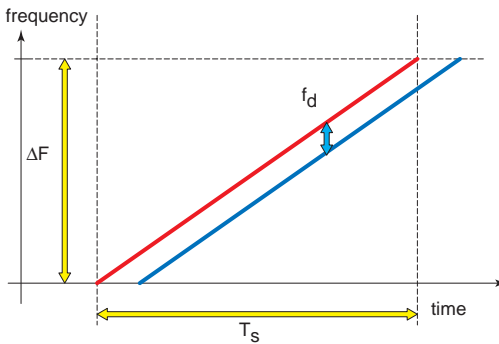
$$f_d \;=\; \frac{\Delta F \times 2R}{T_s \times c}$$

[Eq. 4.1]

ΔF bandwidth
T_s sweep time
R distance
f_d difference frequency
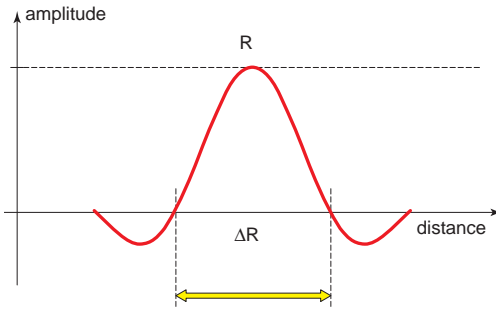c speed of light

Fast Fourier Transform

The FAST FOURIER TRANSFORM produces a frequency spectrum of all echoes such as that at f_d.
There is an ambiguity Δf_d for each echo f_d.

$$\Delta f_d \;=\; \frac{2}{T_s}$$

[Eq. 4.2]

The ambiguity of the distance R, is ΔR

Fig 4.24 to 4.26 - FM - CW range resolution

$$\frac{\Delta R}{R} = \frac{\Delta f_d}{f_d}$$

$$\frac{\Delta R}{R} = \frac{\dfrac{2}{T_s}}{\dfrac{\Delta F \times 2\,R}{T_s \times c}}$$

$$\frac{\Delta R}{R} = \frac{c}{\Delta F \times R}$$

$$\Delta R = \frac{c}{\Delta F}$$

[Eq. 4.3]

From equation 4.3, it can be seen that with an FM - CW radar the range resolution ΔR is equal to:-

$$\frac{c}{\Delta F}$$

Therefore, the wider the bandwidth, the better the range resolution.
Examples:

A linear sweep of 2 GHz has a range resolution of 150 mm whereas a 1 GHz bandwidth has a range resolution of 300 mm.

In process radar applications, each echo on the frequency spectrum is processed with an envelope curve. The above equations (Equations 4.1 to 4.3) show that the Fast Fourier Transforms (FFTs) in process radar applications do not produce a single discrete difference frequency for each echo in the vessel. Instead they produce a difference frequency range Δf_d for each echo within an envelope curve. This translates into range ambiguity.

FM - CW frequency spectrum - bandwidth and range resolution

Frequency spectrum - narrow bandwidth of linear sweep
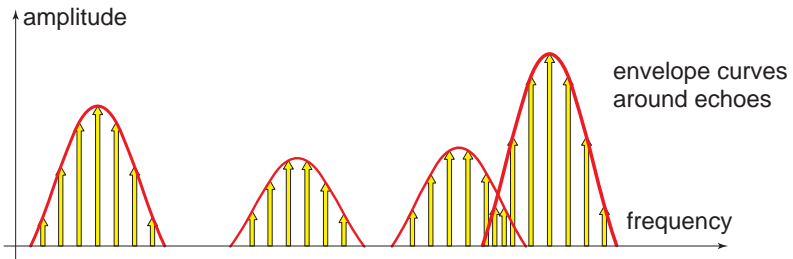
Frequency spectrum - wide bandwidth of linear sweep
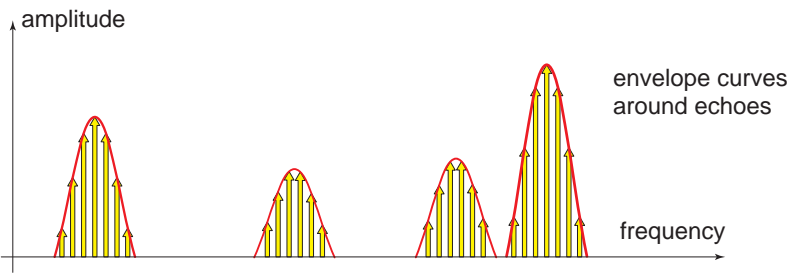
Fig 4.28   Illustration of envelope curve around the frequency spectrum of FM - CW radars. The same four echoes are shown for radar transmitters with different bandwidths. An improvement in the range resolution is achieved with a wider bandwidth of the linear sweep

Other influences on accuracy

As we have demonstrated, FM - CW and PULSE process radar transmitters use an envelope curve for measurement. A wider bandwidth produces better range resolution. The correspondingly short echo will have a steep slope and therefore a more accurate measurement can be made. Other influences on accuracy include signal to noise ratio and interference.

A high signal to noise ratio allows more accurate measurement while interference effects can cause a disturbance of the real echo curve leading to inaccuracies in the measurement.

Choice of antenna and mechanical installation are important factors in ensuring that the optimum accuracy is achieved.

High accuracy radar

High accuracy of the order of $\pm$ 1 mm is generally meaningless in an active process vessel or a solids silo. For example, a typical chemical reactor will have agitators, baffles and other internal structures plus constantly changing product characteristics.

Although custody transfer level measurement applications are not in the scope of this book, this section discusses how a higher accuracy can be achieved.

Pulse radar

For most process applications, measurement relative to the pulse envelope curve is sufficient. However, if the liquid level surface is flat calm and the echo has a reasonable amplitude, it is possible to look inside the envelope curve wave packet at the phase of an individual wave.

However, the envelope curve of a high frequency radar with a short pulse duration is sufficiently steep to produce a very accurate and cost effective level transmitter for storage vessel applications.
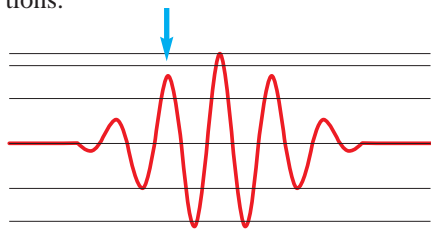
Fig 4.29 *Higher accuracy of pulse radar level transmitters can be achieved by looking at the phase of an individual wave within the envelope curve. This is only practical in slow moving storage tanks*

FM - CW radar

The fundamental requirement for an accurate FM - CW radar is an accurate linear sweep of the frequency modulation.

As with the pulse radar, it is possible to look inside the envelope curve of the frequency spectrum if the application has a simple single echo that is characteristic of a liquids storage tank. This is achieved by measuring the phase angle of the difference frequency. However, this is only practical with custody transfer applications where fast and expensive processors are used with temperature and pressure compensation.
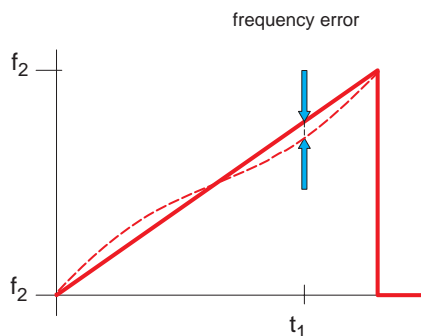
Fig 4.30 *It is essential that the linear sweep of the FM - CW radar is accurately controlled*

Power

Microwave power

Radar is a subtle form of level measurement. The peak microwave power of most process radar level transmitters is less than 1 milliWatt. This level of power is sufficient for tanks and silos of 40 metres or more.

The average power depends on the sweep time and sweep repetition rate of FM - CW radar and on the pulse duration and pulse repetition frequency of pulse radar transmitters.

An increase in the microwave power will produce higher amplitude echoes. However, it will produce higher amplitude false echoes and ringing noise as well as a higher amplitude echoes off the product surface. The average microwave power of a Pulse radar can be as little as 1 microWatt.

Processing power

FM - CW radars need a high level of processing power in order to function. This processing power is used to calculate the FFT algorithms that produce the frequency spectrum of echoes. The requirement for processing power has restricted the ability of FM - CW radar manufacturers to make a reliable two wire, intrinsically safe radar transmitter.

Pulse radar transmitters work in the time domain without FFT analysis and therefore they do not need powerful processors for this function.

Safety

The low power output from microwave radar transmitters means that they are an extremely safe method of level measurement.

Two wire, loop powered radar

Pulse radar

The low energy requirements of pulse radar enabled the first ever two wire, loop powered, intrinsically safe radar level transmitter to be introduced to the process industry in mid-1997. The VEGAPULS 50 series of pulse radar transmitters have proved to be very capable in difficult process conditions. The performance of the two wire, 4 to 20 mA, sensors is equal to the four wire units that preceded them.

The pulse microwave module only needs a 3.3 volt power supply with a maximum power consumption of 50 milliWatts. This drops down to 5 milliWatts when it is in stand-by mode. The difference between the two wire pulse and the four wire pulse is that the two wire radar sends out bursts of pulses and updates the output about once every second. The four wire sends out pulses continuously and updates seven times a second.

With high quality electronics, the complete 24 VDC, 4 to 20 mA transmitter is capable of operating at only 14 VDC. This allows it to directly replace existing two wire sensors.

Pulsed FM - CW

The low power requirements of pulse radar have allowed two wire radar to become sucessful. FM - CW radar requires processing power and time for the FFT's to be calculated. Power saving has been used to produce a 'pulsed' FM - CW radar. However, this device is limited to simple storage applications because the update time is too long and the processing too limited for arduous process applications.

4. Radar level measurement

Summary of radar level techniques

FM - CW (frequency modulated continuous wave) radar

- Indirect method of level measurement
- Requires Fast Fourier Transform (FFT) analysis to convert signals into a frequency spectrum
- FFT analysis requires processing power and therefore practical FM - CW process radars have to be four wire and not two wire loop powered
- FM - CW radars are challenged by large numbers of multiple echoes (caused by the parabolic effects of horizontal cylindrical or dished topped vessels)

PULSE radar

- Direct, time of flight level measurement
- Uses a special sampling technique to produce a time expanded intermediate frequency signal
- The intermediate frequency is produced in hardware and does not require FFT analysis
- Low processing power requirement mean that practical and very capable two wire, loop powered, intrinsically safe pulse radar can be used in some of the most challenging process level applications