# FMCW Radar Sensors

## Frequency Modulated Continuous Wave Radar

### Basic operating principles and theory

FMCW (Frequency Modulated Continuous Wave radar differs from pulsed radar in that an electromagnetic signal is continuously transmitted. The frequency of this signal changes over time, generally in a sweep across a set bandwidth. The difference in frequency between the transmitted and received (reflected) signal is determined by mixing the two signals, producing a new signal which can be measured to determine distance or velocity. A sawtooth function is the simplest, and most often used, change in frequency pattern for the emitted signal.

FMCW radar differs from classical pulsed radar systems in that an RF signal is continuously output. Consequently, time of flight to a reflecting object can not be measured directly. Instead, the FMCW radar emits an RF signal that is usually swept linearly in frequency. The received signal is then mixed with the emitted signal and due to the delay caused by the time of flight for the reflected signal, there will be a frequency difference that can be detected as a signal in the low frequency range. A schematic presentation is shown in Figure 1.

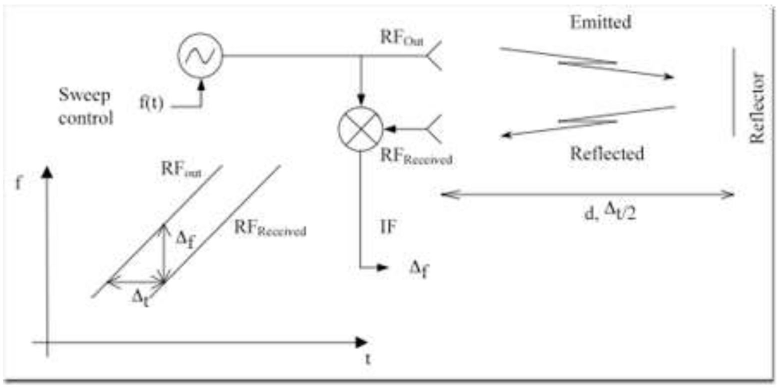


Figure 1. Schematic presentation showing how a low frequency signal is generated by mixing the received RF signal with the output RF signal. Due to the delay, Δt, caused by emitted signal



Sivers IMA AB
Box 1274
SE-164 29 Kista
Sweden

Tel: +46-8-703 68 00
Fax: +46-8-751 92 71
e-mail: sales@siversima.se
www.siversima.com

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traveling the distance to the reflector and back to the receiver, there will be a small difference in signal frequency between the two RF signals. This is output as an IF-signal with frequency Δf.

A simplified derivation of the intermediate frequency (IF) signal with the frequency Δf can be made in the following way: assume that the RF signal generator will output a frequency that is changing linearly over time as:

$$f_{RFOut} = f_{RF0} + k_f * t,\ 0 \le t < T \qquad \text{eq. 1}$$

where $f_{RF0}$ is the starting frequency, T is the frequency sweep time and $k_f$ is the slope of the frequency change, i.e. the sweep rate:

$$k_f = \frac{BW}{T} \qquad \text{eq. 2}$$

where BW is the frequency sweep bandwidth. The delay caused by the round-trip of the emitted signal to the reflector is calculated as:

$$\Delta t = 2\frac{d}{c} \qquad \text{eq. 3}$$

where d is the distance between the radar antenna and the reflector and *c* is the speed of light. Due to the delay, the frequency of the received signal compared with the emitted signal will be:

$$f_{RF\,Received} = f_{RF0} + k_f * (t - \Delta t),\ \Delta t \le t < T + \Delta t \qquad \text{eq. 4}$$

The difference in frequency, Δf, between $f_{RF\ Received}$ and $f_{RF0}$ is thus:

$$\Delta f = k_f * (-\Delta t) \qquad \text{eq. 5}$$

This is the signal that is output from the detector. The minus sign can be omitted since the real signal frequency output from the radar detector is wrapped to a positive frequency. Thus the expression can be written as:



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$$\Delta f = \frac{BW}{T} \cdot 2\frac{d}{c}, \qquad \text{eq. 6}$$

Typical values for the RS3400 series modules would be a frequency sweep, BW, of 1500 MHz over T=75 ms corresponding to a sweep rate, $k_f$, of 20 000 MHz/s. A distance, d, between the radar and a reflector of 15 m would give a delay, Δt, of 0.1 µs and the IF signal frequency, Δf, would then be 2000 Hz. This signal is easily sampled with a high resolution ADC in order to be detected. If several reflectors are appearing in the measurement setup, the resulting IF signal will contain superpositions of the individual IF-signals from the echoes.

Different echoes are distinguished by their unique IF signal frequency and a Fourier transform of the sampled signal can be used to extract the distances to the different targets. The measurement range of the system is limited by the sensitivity of the detector and the sampling rate of the ADC. For the RS3400 series a sampling rate of 20 kHz gives a maximum detectable IF signal frequency of 10 kHz, which corresponds to a range of 75 m. Longer ranges are easily achievable by either increasing the sample rate or lowering the sweep rate. In addition, antenna gain needs to be fairly high in order to provide sufficient signal levels for the detector.

## Theoretical performance

The fundamental range measurement resolution of the system can be estimated as follows. The Fourier transform of a time limited signal can only detect an IF signal frequency with a resolution of 1/T, keeping in mind that Δt<<1/T; thus the sampling time can be approximated by T. Using equation 6, this gives the minimum change in d, Δd, as:

$$\frac{1}{T} = \frac{BW}{T} \cdot 2\frac{\Delta d}{c}, \qquad \text{eq. 7}$$

which can be transformed to:

$$\Delta d = \frac{c}{2BW}, \qquad \text{eq. 8}$$



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showing that the range measurement resolution is only limited by the sweep bandwidth. This is an important observation since it is says that resolution is not dependent on the frequency of the RF signal itself, but rather only on the sweep bandwidth. There are methods of increasing the resolution of the measurements by a factor of 10 to 100 using fitting algorithms. These find a peak in the IF signal spectrum which is not at an integer frequency point defined by the sampling rate and sweep bandwidth.

The range detection and FMCW radar principle may also be derived using a characterization of the IF signal phase rather than the frequency. This is recommended in order to understand the possibilities of a discrete system where the frequency sweep really is generated by a discrete set of frequencies. This derivation also lends itself more directly to high resolution range measurements. For the simplicity of understanding the measurement principle it is however unnecessary and is thus included as an appendix.



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# Applications

FMCW radars in the GHz spectrum provide excellent distance measurement performance in applications where high accuracy, repeatability and reliability are needed. Because of the short wavelength (12 mm for a 24 GHz signal), resolutions on the order of 2 cm can be achieved over distances of 20-30 meters. This allows FMCW sensors to excel in applications such as tank level gauging where high resolution non-contact measurements are needed.

FMCW sensors have been used in oil and LNG tankers and storage tanks to measure product volumes, in commercial, military, and unmanned aircraft as altimeters, and in industrial applications for the verification of product dimensions in automated systems.

Due to to the non-contact nature of the measurement system, and due to the nature of the microwave, FMCW radar operating in the GHz range also exhibit excellent resistance to dust, steam, heat, etc. This allows for use in conditions as demanding as those found in the blast furnace of a steel mill.

Due to their ability to determine range over very short or fixed distances, FMCW based systems have also been in transportation applications, including automotive collision avoidance radars and marine radars. Other applications have included wall-penetrating radar for imaging and detection, security sensors against intrusion, and human vital-sign detection and measurement. In summary, radar sensors using FMCW principles perform extremely well in situations requiring non-contact measurement of distance in harsh conditions.



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# Competing technologies

**Infrared**

Advantages: Good at detecting orthogonal and tangential movement, with wide field of view and low cost

Disadvantages: Poor at detecting radial movement, can have difficulty in diminished visibility conditions such as rain or dust, can not be used to detect range, direction, or speed of objects. Requires a high-quality transparent window for the sensor, making the system more difficult to conceal. The sensor can also be affected by dirt or moisture on the window or in the atmosphere.

**Ultrasound**

Advantages: Relatively accurate at short ranges, triangulation possible, low cost

Disadvantages: Tends to have a very low range. Provides no velocity information. Requires a visible sensor. Can be influenced by environmental factors such as noise, wind and temperature

**Radar (pulsed)**

Advantages: Proven technology with long history. Long detection ranges possible using high power systems. Can be designed to deal with nearby reflectors and interference relatively easily.

Disadvantages: High peak power output and radiation. Has difficulty with measurements at short ranges due to short signal travel time. More difficult to eliminate clutter. Can take time to “warm up”.

**Laser**

Advantages: Highly directional. Quick start up and measurement. Excellent for range finding. More difficult to detect or jam. Relatively low cost.

Disadvantages: Can be affected by atmospheric conditions including fog, rain and temperature. Does not work well on all surfaces. Limited field of view can prevent detection of multiple targets.



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# FMCW Radar Sensors

**Cameras/Video**

Advantages: Highly flexible, can be programmed to recognize different objects, not just range and velocity. Sensors can be low cost.

Disadvantages: Requires clear field of view, can be affected by shadows or bad weather, etc... Requires complicated software and powerful hardware



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# FMCW Radar Sensors

# Advantages and disadvantages of FMCW radar

## Advantages

### High resolution distance measurement

Mm-wave FMCW radars can have very high resolution for ranging, velocity and imaging application. A distance measurement resolution of 2 cm can be easily achieved over 20-30 meters. Accuracy for non-moving targets is better than for moving targets, and requires less processing power. Measurements of moving targets are of course possible, but requires more powerful algorithms and hardware. Other technologies such as infrared or ultrasonics cannot detect range or only over very limited distances.

### Quick updating of measurement

Because FMCW mm-wave radars are continuously transmitting a signal, there is little delay in measurement updates, as can be the case with pulsed systems. Additionally, solid state electronics produce almost instantaneous start up times, as compared to pulsed systems often using magnetrons. Systems based on lasers, ultrasonics, or infrared will have similar update speeds to FMCW systems.

### Functions well in many types of weather and atmospheric conditions

Due to the short wavelength of the electromagnetic radiation used, mm-wave systems have excellent performance in rain, humidity, fog and dusty conditions. The short wave-length means that raindrops, water vapor or dust particles do not block wave propagation easily. Heavy rain is generally required before a reduction in range or resolution occurs. mm-wave systems will function identically during day or night. FMCW radars are also immune to effects from temperature differences, or high temperatures.



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**Better electrical and radiation safety**

Sivers IMA modules are designed to be inherently safe, for use in an explosive atmosphere such as an oil tanker or LNG storage facility. They are completely sealed and tested, so there is no risk of sparking, resulting in fire or explosion.

Compared to pulsed radar systems, the peak emitted electromagnetic radiation is far lower in a FMCW radar system. This is important in applications where people are close to the antenna, as the peak emitted energy is far lower. This allows for more flexibility in selecting a mounting location for the antenna. The lower peak power requirements also allow for lower power consumption in the supporting electronics, resulting in lower costs and technology needs.

Infrared and video based systems are passive systems, and therefore do not emit a signal for measurement purposes. Most laser based ranging systems use low power emitters, and are considered eye-safe.

**Good range compared to other non-radio technologies**

Compared to systems operating in the visible or infrared light spectrum, or those using ultrasonic waves, FMCW radar sensors have excellent measurement range due to superior signal propagation.

**Can be mounted invisibly (behind radome)**

FMCW mm-wave radar systems can be mounted behind a wide variety of radio-transparent materials including most plastics and fiberglass. This allows for use in applications where the sensor must concealed for security, weather resistance or aesthetic reasons.

**Can penetrate variety of materials**

Mm-waves are capable of penetrating a variety of non-metallic materials. These can include wood, concrete, various polymers and composites. This allows mm-wave based systems to be easily concealed, or to be used for measurement or detection of concealed or covered targets. All other non-microwave based systems require an exposed sensor or window to functions, and can not penetrate a majority of materials.



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**Better at detecting tangential motion than Doppler based systems**

Since FMCW based systems do not require movement towards or away from the antenna to detect range, an 2D or 3D FMCW based system will be better at detecting tangential or orthogonal movement compared to Doppler-pulse systems when used in a scanning capacity.

Infrared and video based systems are also excellent at detecting movement, but may not be able to quantify the direction or magnitude of the movement.

## Disadvantages

**Reduced range compared to pulse radar**

Due to the generally lower peak power output of FMCW radar systems, their long range performance can be lower than compared to pulsed systems. Since the transmitted signal is not as strong the received signal will be attenuated by atmospheric effects, interference, and distance. FMCW radars are however competitive or superior to other competing technologies in range.

**More expensive than competing technologies**

Similar economies of scale have not been achieved in FMCW systems compared to pulsed and Doppler radar systems, due to the maturity of the existing technologies in the marketplace. Sivers IMA FMCW radar modules are however price competitive, and can be produced in large, commodity-scale volumes. Additionally, the module uses a standard 3-wire interface for control functions, allowing for easier integration, and less expensive R&D. Compared to infrared and ultrasonic systems, FMCW systems will generally be far more expensive.

**Susceptible to interference from other radio devices**

Because they are continuously transmitting across a frequency band, FMCW systems may be more susceptible to interference from other electronic systems. This is due to the larger range of frequencies encountered and due to the lower "peak" power, resulting in the returned signal being overwhelmed by other emissions. Pulsed systems can generally overcome interference by increasing transmitted power or by switching frequencies. Distance measurement or detection systems using infrared, video, or lasers are generally immune to interference, given their operating principles.



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